This publication was withdrawn on 17 June 2025.

This document has been replaced by the National Framework for Water Resources 2025: water for growth, nature and a resilient future.

Appendix 1: Explanation of modelling approach and assumptions made

Water resources national framework

16 March 2020

Version 1

We are the Environment Agency. We protect and improve the environment.

We help people and wildlife adapt to climate change and reduce its impacts, including flooding, drought, sea level rise and coastal erosion.

We improve the quality of our water, land and air by tackling pollution. We work with businesses to help them comply with environmental regulations. A healthy and diverse environment enhances people's lives and contributes to economic growth.

We can't do this alone. We work as part of the Defra group (Department for Environment, Food & Rural Affairs), with the rest of government, local councils, businesses, civil society groups and local communities to create a better place for people and wildlife.

Published by:

Environment Agency
Horizon House, Deanery Road,
Bristol BS1 5AH

www.gov.uk/environment-agency

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Contents

1. Introduction

The national framework sets out the challenge for water resources over the next generation. As part of this, we have worked closely with the University of Manchester and the University of Oxford to use the models they have developed on future water needs. We have also used the data from water company water resource management plans to develop a national water resources supply demand model to explore the impact of different future scenarios around water efficiency, leakage, levels of drought resilience and reductions in abstraction to improve the environment.

This appendix provides further background to the modelling results presented in the main report. It is intended for those interested in the modelling who want to know more details around the data, the approaches used and the results obtained.

The national water resources supply demand model was primary based on data from the water company 2019 Water Resources Management Plans (WRMP19). The main the focus was on the period 2025 to 2050, with the data extended out to 2100. Section 2 of this document provides more information on the data collation and checking undertaken, the representations of the main drivers of change and the options to resolve future issues around water availability, including climate change, increased resilience to drought, population growth and sustainability reductions.

Our work with the University of Manchester has allowed us to explore the sensitivity of the factors affecting changing water needs and to look at how different types of solutions, particularly water supply and water transfer options, compare when optimised by cost. This includes looking at possible transfer options not yet scoped by the water industry. More details are given in section 3.

We have worked with the University of Oxford to explore the impacts of climate change on drought and, in turn, the impacts that drought is likely to have on the water supply network. This work has used a large number of climate change scenarios, a new national hydrological model developed by the University of Bristol, and the University of Oxford's water resource system simulation model of England and Wales. This was originally developed for the Water UK Long term Water Resources Planning Framework and has since been improved with cooperation from water companies. More details are given in section 4 of this document.

We plan to continue to build our understanding of future water needs and to continue our work with leading universities with the aim to develop a national model that includes a more sophisticated representation of national water resources supply infrastructure. We will use this model to support and challenge regional plans and inform our advice to government on the plans that come forward. The different modelling approaches described in the appendix will provide the basis for this.

1.1. Modelling results in the national framework report

Results from the different modelling strategies detailed in this appendix provide an evidence base for several sections of the national framework report. The national water resource supply-demand model described in section 2, informs our understanding around the pressures on public water supply, as well as the options available to meet future public water supply needs, as presented in sections 4, 5, and 9 of the main national framework report. The national water resource supply-demand model for options comparison, developed in collaboration with the University of Manchester and described in section 3 of this appendix, provides insight on how effective different options are for meeting future public water supply needs, as detailed in section 9.3.3 of the main report. Finally, the national water resource system simulation model, developed in collaboration with the University of Oxford and described in section 4 of this appendix, provides evidence around the future pressures on public water supply associated with droughts under climate change, as well as, how water supply options might increase drought resilience. These topics are discussed in sections 5.1.1 and 9.3.2 of the main report, respectively.

While the modelling approaches outlined in this appendix inform different parts of the main national framework report some of them are related to one another. For example, the national water resource supply-demand model for options comparison, outlined in section 3, evolved from the supply-demand model outlined in section 2. These two models are built around the same underlying approach and use the same input data. In contrast, the national water resource system simulation model outlined in section 4, takes a different approach and uses additional datasets.

2. Environment Agency national water resources supply demand model

This section provides more background to the Environment Agency national water resources supply demand model exercise. The national water resources supply demand model was primarily based on the annual data from the water company Water Resources Management Plan 2019 (WRMP19) tables. A spreadsheet was developed to enable the impact of different assumptions around population growth, per capita consumption, resilience to drought and use of drought measures to be explored over the time period 2020 to 2100.

Our central analysis of public water supply pressures and comparison of the solutions available was informed by aggregation of data at the water resource zone (WRZ) level from water company plans. This aggregate approach to modelling balances water supply and water demand using the relevant data for discrete WRZs. The data used in this approach is often derived from other models, for example, future population growth or water availability during different types of drought events. In the WRMP19 tables the water availability and demand values are given as annual single values that represent the design conditions that would be expected if a drought occurred within that year. These are expressed through metrics such as the annual water available during a drought event and the annual water demand during a dry year.

The national water resources supply demand model was used to explore the period between 2025 and 2050. This time period was selected based on the assumption that water companies would have delivered the actions included in the first 5 years of their WRMP19 plans by 2025. The end date was set as most company plans only extend to 2045. The WRMP19 Table data was extended out to 2100 although this did not include any new supply side options not already in WRMP19 preferred plans.

The model results are provided at a regional scale with the actual modelling undertaken at the Water Resource Zone level. This was to enable flexibility in the regional boundaries used. It also enabled a greater understanding of the deficits within a region which can often be hidden by surpluses in other WRZ within a region. Moving water within a region between WRZ in surplus and those in deficit would still require infrastructure development.

The first stage of the modelling exercise was collating and extending the supply and demand WRMP19 data out to 2100. More details on this process are given in sections 2.1 and 2.2.

The population growth data was derived from the data sets developed as part of the CCRA3 programme by Cambridge Econometrics. This provided three population scenarios (high, central and low) out to 2100 at a local authority scale. The method used to convert this information to WRZ level data is described in section 2.3.

Per capita consumption household water use (PCC), expressed in litres per head per day (l/h/d), is the other major component of household demand. A recent Water UK study investigated the impact and uncertainty of a range of water efficiency measures. The results of these studies and how they were used to develop the PCC scenarios for the national water resources supply demand model are described in section 2.4.

Consumption is primarily a function of population growth and PCC. Section 2.5 outlines how non household and household consumption changes with different assumptions around population and PCC.

Climate change will impact upon the water available for abstraction, particularly in the summer and through a shorter period for groundwater sources to refill. It will increase water demand and affect environmental water requirements. Section 2.6 describes how the potential climate change was incorporated into the national water resources supply demand model.

The Water Industry National Environment Programme (WINEP) outlines the actions needed to be undertaken by water companies to address unsustainable abstraction, such as from chalk streams. Currently the WINEP process is incremental in nature and focusses on actions over the next five years. Section 2.7 describes how some longer term impact scenarios were developed using information from the water company WRMP19. Note, this work is distinct from the additional national modelling on environmental water needs explained in appendix 4.

Water companies in their WRMP19 generally planned to increase drought resilience so that a 1 in 200 year drought event (severe drought) could be managed without the use of rota cuts or standpipes. The National Framework Senior Steering Group has agreed that regional groups should plan on the basis of extending this further so that public water supplies are resilient to a 1 in 500 year drought (extreme drought) and we expect a more formal steer from government on this in the forthcoming National Infrastructure Strategy. Data provided by the water companies in their WRMP19 tables was used to provide a consistent assessment of the water available during severe and extreme droughts. The approached taken is described in section 2.8.

Some companies have included the planned use of drought measures in their WRMP19. This includes drought permits and Temporary Use Bans (TUBs). To improve our ability to compare across companies, the impact of drought measures was removed if it had been included in the company's WRMP19 analysis, and subsequently consistent assumptions added back in for all companies. This used the data in the WRMP19 tables where possible in order to create a more consistent assessment of water availability across the water companies and WRZ. The approach is described in section 2.9.

The water industry in England is planning to reduce leakage by 50% by 2050 as compared to the leakage volumes in 2017 to 2018. Details of the leakage volumes used for the different scenarios are given in section 2.10.

Within their WRMP19 water companies have identified a number of preferred schemes to enable them to achieve a positive balance between the water available and expected water demand. A summary of these schemes is given in section 2.11.

A spreadsheet was developed bringing together all the above data to allow different components to be adjusted. An overview of the national water resource supply demand model is given in Section 2.12. More details of the scenarios are given in Section 2.13.

2.1. Extraction of data from WRMP19 tables

The water company WRMP are focused on ensuring that water companies can meet customer water needs over at least the next twenty five years. The first stage is to predict what would occur if existing polices and operations continued but no new supply or demand actions were undertaken, this is the WRMP19 baseline forecast. If there is a shortfall between future water availability and demand, the company needs to identify feasible options to address the shortfall. The preferred feasible options are selected and added to the baseline to produce a final plan.

The water company's water resources management plan (WRMP) contains a series of data tables at water resource zone level. These tables present the supply-demand balance of the plan, information on possible options and some of the key supporting information. The data provided in the tables is for a single WRZ specific design case, for example the worst drought on record.

The information required from water companies, which we have used in the national water resources supply demand model, is set out in 10 tables. These are summarised in table 1 below:

Table 1: Summary of the WRMP19 Tables content. BL denotes baseline, FP denotes Final Plan

Title page - basic company, resource zone, and planning scenario details
Resource zone summary - graphical information taken from the rest of the tables.
1. BL Licences - licensed abstraction quantities and associated water available.
2. BL Supply – initial information on supply components.
3. BL Demand – initial information on demand components
4. BL SDB – bring together initial demand and supply data to identify any water shortfall
5. Feasible options – cost and impact of feasible water management options
6. Preferred options – water supply/demand impact of preferred options
7. FP Supply – update supply component information with preferred supply options impact
8. FP Demand – updated demand components with preferred demand option impact
9. FP SDB – final supply vs demand balance
10. Drought plan links – impact of different droughts on supply and demand

For their WRMP19 tables the water companies were given a standard set of data tables to complete. They were also given the opportunity to adjust those tables if these adjustments were documented in their plan. This led to a number of different variations of tables across the water companies.

The Environment Agency developed an extraction tool to take the data from the WRMP19 tables, check for variations against the standard data tables and create a new set of tables in a standard format. The data from WRMP19 tables 1 to 9 were split into three components: the supply and demand data from table 1 to 3 and 7 to 9, summary feasible option data from table 5, and preferred option data from table 6. There was a set of these tables for each WRZ and for the draft, revised draft and final plan data table submissions. The information from table 10 from all WRZs was collated.

The checked data sets from the revised WRMP19 tables were used as the basis of our analysis.

2.2. Extension of supply demand data

Most companies provided WRMP19 data out to 2044/45, with two providing data out to 2079/80. The end dates for WRMP19 table data for each water company is shown in table 2.

Table 2: End date of water company WRMP19 table data

Water Company	End Year	Water Company	End Year	Water Company	End Year
Affinity Water	2080	Portsmouth Water	2045	SES Water	2080
Anglian Water	2045	Severn Trent Water	2045	Thames Water	2080
Bristol Water	2045	South East Water	2080	United Utilities	2045
Cambridge Water	2045	South Staffordshire Water	2045	DCWW	2045
Essex & Suffolk Water	2060	South West Water	2045	Wessex Water	2045
Northumbrian Water	2060	Southern Water	2070	Yorkshire Water	2045

Using a mixture of linear regression and no change assumptions all the data sets were extended out to 2100. The population dataset used was the high population scenario derived from the Cambridge Econometrics data (see section 2.3). Table 3 summarises how the different supply demand components were extended, if the component is not listed it was assumed to be constant after the last year of WRMP19 data. The principle was to keep the extrapolation as simple as possible with a focus on population and the impact of new house metering on per capita consumption.

2.3. Population

The population forecasts used in the national framework are part of a larger socioeconomic dataset created by Cambridge Econometrics, for the 3rd Climate Change Risk Assessment project (CCRA3; in this document referred to as the Cambridge Econometrics dataset). The forecasts follow three growth rate scenarios (high central and low), ranging from 2016 to 2100. These are underpinned by official datasets published by the Office of National Statistics (ONS). Population projections from the ONS are based on assumptions around future levels of fertility, mortality and migration, which differ according to each variant of the central projection. Assumptions intrinsic to each scenario are explained in more detail below.

Population growth is accounted for in the water company plans and WRMP tables, however, most companies plan out to 2045 and therefore the Cambridge Econometrics dataset was used to estimate the long-term (2100) growth rates more accurately. Furthermore, the water company plans follow the high population growth scenario, to avoid limiting development and economic growth within a region. The national framework sets out to understand the future pressures on public water supply and account for any associated uncertainty. In this way, the lower growth rate scenarios (low and central) from the Cambridge Econometrics dataset were used to investigate the uncertainty around population growth based on a consistent set of projections.

Table 3: Summary of WRMP19 data extension

ID	Component	Extrapolation method after last year of data
7BL/7FP	Deployable Output	Assumed constant after last year of data, 7FP adjusted for any 8BL changes
8BL	Changes to Deployable Output	Sum of 8.1BL to 8.3BL
8.1BL	Change in DO due to CC	Linear forecast from last 10 years of data
8.3BL	Total other changes to DO	Linear forecast from last 10 years of data
19BL/19FP	Water delivered measured non HH	Measured Non-HH Consumption (23) plus the Measured Non-HH USPL (34)
20BL/20FP	Water delivered unmeasured Non-HH	Un-measured Non-HH Consumption (24) plus the Measured Non-HH USPL (35)
21BL/21FP	Water delivered measured HH	Measured HH Consumption (25) plus the Measured Non-HH USPL (36)
22BL/22FP	Water delivered unmeasured HH	Un-Measured HH Consumption (26) plus the Measured Non-HH USPL (37)
25BL/25FP	Measured HH Consumption	Measured HH population (51) multiplied by the Measured HH PCC (29)
26BL/26FP	Unmeasured HH Consumption	Un-Measured HH population (52) multiplied by the Un-Measured HH PCC (30)
27	% consumption driven by CC	Linear forecast from last 10 years of data
28	Volume of consumption driven by CC	Consumption (23 to 26) multiplied by % of consumption driven by CC (27)
29BL/29FP	Measured HH PCC	Linear forecast from last 10 years of data, set to be between 90-200
30BL/30FP	Unmeasured HH PCC	Linear forecast from last 10 years of data, set to be between 110-230
31BL/31FP	Average Household PCC	Total HH consumption (25+26) divided by total household population (49+50)
36BL/36FP	Measured HH USPL	USPL per measured HH property constant from last year of data

ID	Component	Extrapolation method after last year of data
37BL/37FP	Unmeasured HH USPL	USPL per un-measured HH property constant from last year of data
39BL/39FP	Distribution Losses	Total Leakage (40) minus all the USPL components (34,35,36,37 and 38)
40BL/40FP	Total Leakage	If required linear forecast from last 10 years of data to 2050 then no change
41BL/41FP	Total Leakage l/prop/day	Total Leakage (40) divided by Total Resource Zone properties (48)
45BL/45FP	Total measured HH prop no void	previous year plus the sum of 45.1 to 45.6
45.1BL/FP	New properties	Annual Pop (53) increase divided previous year measured HH occ rate (54)
45.2BL/FP	Meter optants properties	Linear forecast from last 10 years of data never goes below 0.0
45.3BL/FP	Compulsory metering properties	Linear forecast from last 10 years of data never goes below 0.0
45.4BL/FP	Metering change occupancy prop	Linear forecast from last 10 years of data never goes below 0.0
45.5BL/FP	Selective metering properties	Linear forecast from last 10 years of data never goes below 0.0
45.6BL/FP	Other changes to metered properties	Linear forecast from last 10 years of data never goes below 0.0
45.7BL/FP	Measured void HH properties	Sum of 45.7 & 47 fixed at last year value but vary with % meter
46BL/46FP	Unmeasured HH properties no void	Subtracting 45.2, 45.3, 45.4 and 45.5 from previous year total
47BL/47FP	Unmeasured void HH properties	Sum of 47 & 45.7 fixed at last year value but vary with % meter
48BL/48FP	Resource Zone Prop incl voids	Sum of 42,43,45,46,44,45.7 and 47
51BL/51FP	Measured HH Population	previous year measured HH population (51), plus annual population increase (53) all to new metered properties (45.1), Unmeasured HH moved to measured HH (45.2,45.3,45.4, 45.5) multiplied by Un-measured HH occupancy rate (55) from the previous year, and other change in existing measured HH (45.6) multiplied by the previous year Measured HH occupancy rate (54)

ID	Component	Extrapolation method after last year of data
52BL/52FP	Unmeasured HH Population	Previous year minus movement of unmeasured HH to measured HH (45.2,45.3, 45.4, 45.5) times the previous year Un-measured HH occupancy rate (55)
53BL/53FP	Total Resource Zone Population	linear forecast from last 10 years of data (high pop growth)
54BL/54FP	Measured HH Occupancy Rate no voids	Measured HH Population (51) divided by measured HH properties no void (45)
55BL/55FP	Unmeasured HH - Occupancy Rate	Un-Measured HH Pop (52) divided by the Un-Measured HH Properties no void (47).
56BL/56FP	% HH Metering penetration no voids	Measured HH properties no void (45) divided by Total HH prop no void (45+56), 95% max
57BL/57FP	% HH Metering penetration with voids	Measured HH properties no void (45) divided by Total HH prop (45+45.7+46+47).
11BL/11FP	Distribution input	sum of 19+20+21+22+32+33+38+39
12BL/12FP	Water Available For Use	sum of 7+8 minus sum of 9+10
13BL/13FP	Total Water Available For Use	Water available for use (12) + water imported (2+3) - water exported (5+6)
14BL/14FP	Target headroom - CC component	Linear forecast from last 10 years of data, but is not allowed to decrease
16BL/16FP	Target Headroom	Target headroom - CC component (14) plus other components (15)
17BL/17FP	Available Headroom	Total Water Available (13) for Use minus Distribution Input (11)
18BL/18FP	Supply Demand Balance	Available Headroom (17) minus Target Headroom (16)
If the component is not listed it was assumed to be constant after last year of data		

The central population projection in the Cambridge Econometrics dataset is based on the ONS ‘principal population scenario’, which assumes demographic patterns in future such as fertility, mortality and migration trends remain the same as current trends. The central scenario assumes that the UK population grows at a steady pace, increasing by over 17 million (compared to 2016), to reach a total population of almost 83 million in 2100. In this scenario, the short term (i.e. up to 2026), just under half the UK population growth is expected to result from more births than deaths, with the remainder of the increased population resulting from net migration. It is assumed these trends continue up to 2100.

In the central scenario the UK population is ageing, with older people accounting for an increasing share of the population. Up to 2050 the ageing population is partly caused by the 1945-1964 baby boom generation reaching retirement age and then moving into old age. By 2100, those aged over 65 are expected to account for around 30% of the total population, compared to 18% in 2016. This is caused by numerous factors, such as increased life expectancy due to improvements in health, medicines and health care technology, and lower birth rates leading to a smaller share of people in the 0-15 age bracket. The working age population represents a smaller share of the total population (55% in 2100 compared to 63% in 2018), meaning there is a high dependency ratio.

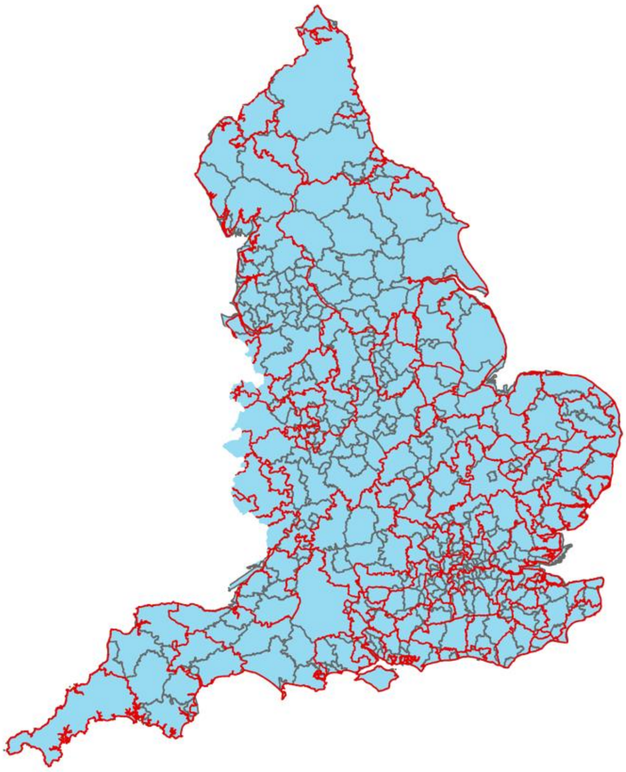
The high population scenario in the Cambridge Econometrics dataset is based on the ONS ‘young age structure’ variant of its principal population projection. This variant projection based on alternative assumptions of future fertility, mortality and migration. In this scenario, fertility rates are assumed to be higher than in the central case while life expectancy is lower. Net migration is higher than in the central case. All these factors lead to a younger age structure of the population. In the high scenario, total population reaches around 92 million in 2100, an increase of almost 27 million from 2016, compared to the central scenario in which the population reaches 83 million in 2100. 59% of the population are of working age (between 16 and 64), compared to the central scenario in which 55% of the population is of working age. The proportion of dependents aged between 0-15 is also slightly higher in the high scenario, reflecting higher birth rates, with this group accounting for 19% of the population compared to 17% in the central scenario.

Finally, the low population scenario in the Cambridge Econometrics dataset is based on the ONS ‘old age structure’ variant of its principal population projection. In this scenario, fertility rates are assumed to be lower than in the central case while life expectancy is higher. Furthermore, net migration is lower than the central case. All these factors lead to an older age structure of the population. In the low scenario, total population reaches 66 million in 2100, an increase of just 1 million since 2016, compared to the central scenario in which the population reaches 83 million in 2100. In 2100 individuals aged >65 account for 36% of the population, compared to 29% in the central scenario.

The population forecasts in the Cambridge Econometrics dataset are reported at the local authority scale. In contrast, the data within WRMP tables, which are used as the basis for modelling in the National Framework, are reported at the water resource zone (WRZ) level. WRZs are much larger than local authorities, this juxtaposition of scale is shown in figure 1.

This difference in scale made it difficult to convert the local authority population data for use in WRZ modelling. At the national scale the Cambridge Econometrics high population forecasts compared well with the forecast from WRMP19. At the WRZ scale the converted Cambridge Econometrics local authority scale high population data had significant divergence from the WRMP19 WRZ population data. This was primarily due to the assumption that population was spread evenly across a local authority (i.e. not taking into account urban vs rural area).

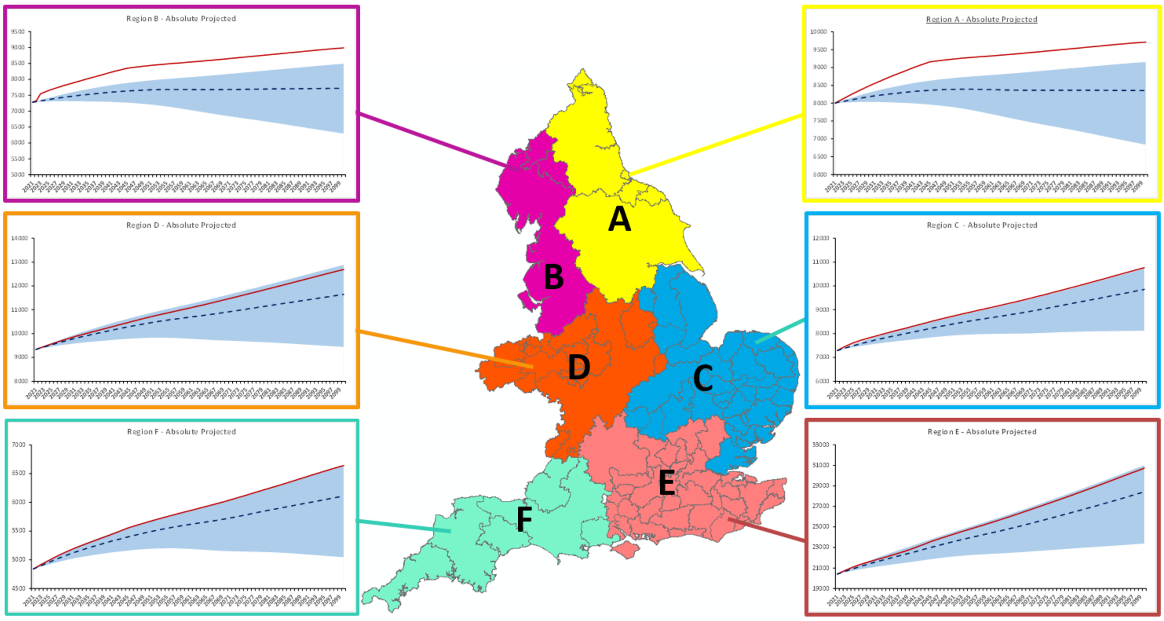
Figure 1: Comparison between spatial extent of local authorities (grey outline) and WRZs (red outline)



In order to work around this problem regional growth rates were used, rather than absolute population numbers. The local authority Cambridge Econometrics data was aggregated from local authority to regional level and regional growth rates calculated for each population growth scenario. These calculated regional growth rates were then used to produce three different WRZ population forecast scenarios using the WRMP19 2020 population forecast as a starting point.

The population forecast using these regional growth rates was used to extrapolate the WRMP2019 data out to 2100. This is required since the majority of companies have only provided data out to 2045 and only a few out to 2060, 2070 and 2080. The final population dataset used in the national framework is shown at the regional level in figure 3.

Figure 2: Red = WRMP19 extended out from 2045-2100 using CCRA3 high growth scenario; blue band = WRMP19 scaled by population growth rates from high, central and low Cambridge Econometrics scenarios



2.4. Per Capita Consumption scenarios

A recent Water UK[1] study looked at the savings, costs and benefits of 18 different demand side interventions including metering, water efficiency labelling of water using products and home audits. Using different mixes of the interventions, six scenarios were developed that covered a range of potential outcomes and the relative roles of water companies and government (see table 4). The per capita consumption savings associated with each scenario and intervention were calculated for each water company in England and Wales from 2020 at five year intervals to 2050 and then 2065.

[1] Pathways to long-term PCC reduction, Water UK (2019)

Table 4: Interventions included in each of the Water UK scenarios

	Extended	Enhanced-01	Enhanced-02	Enhanced-03	Enhanced-04	Water Labelling Only
Progressive metering by region - auto-switched					X	
Progressive metering by region - voluntary	X		X	X		
Innovative tariffs			X		X	
Targeted assisted audits			X		X	
Leaky loo find and fix	X				X	
Water labelling - with minimum standards				X		X
Water labelling - No minimum standards		X				
Community wastewater recycling			X		X	
Increased media campaigns and schools education*	X		X			

Figure 3 shows the derived average regional PCC in 2050 for each of the six Water UK report scenarios. This shows that the average PCC for England could be as low as 87.2 l/person/day. There is a high geographic variation of PCC around England due to a range of factors including; occupancy, age of occupants, property type, socio-demographic factors, metering and the methods used to measure and estimate household consumption. It is therefore to be expected that there would be regional differences.

The Water UK project considered the risk associated with delivering the water use reduction scenarios presented. These risks can be mitigated through adaptive water resources planning and regulation interventions as required. The range of predicted PCC uncertainty in 2050 for the different Water UK scenarios can be seen in figure 4.

Figure 3: Regional average PCC for different Water UK scenarios

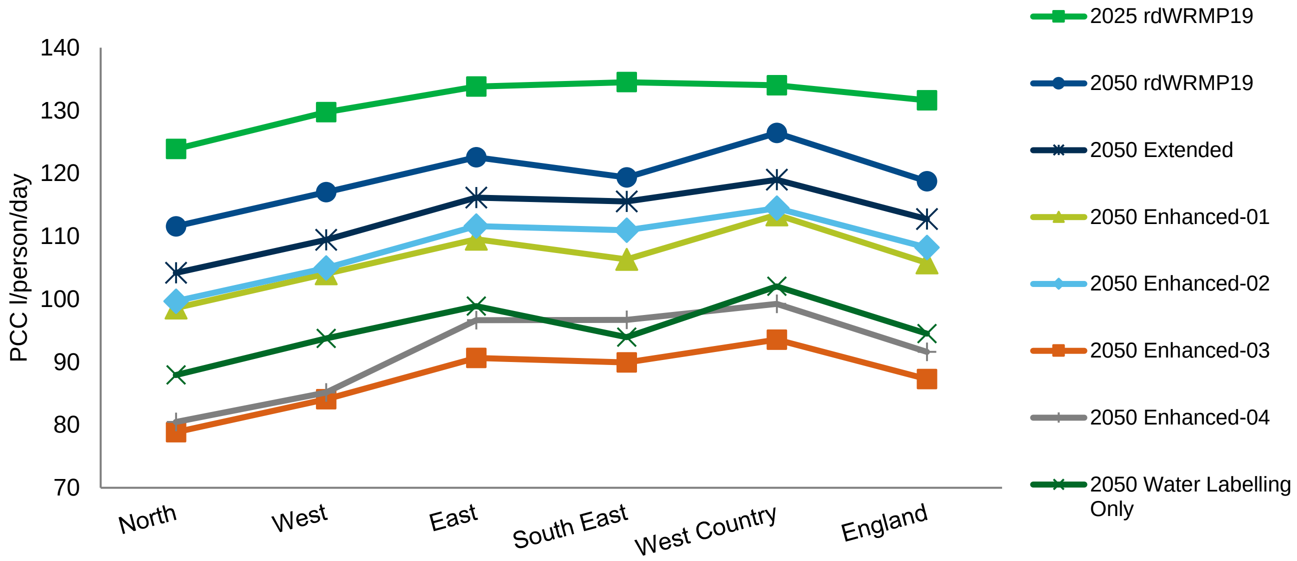
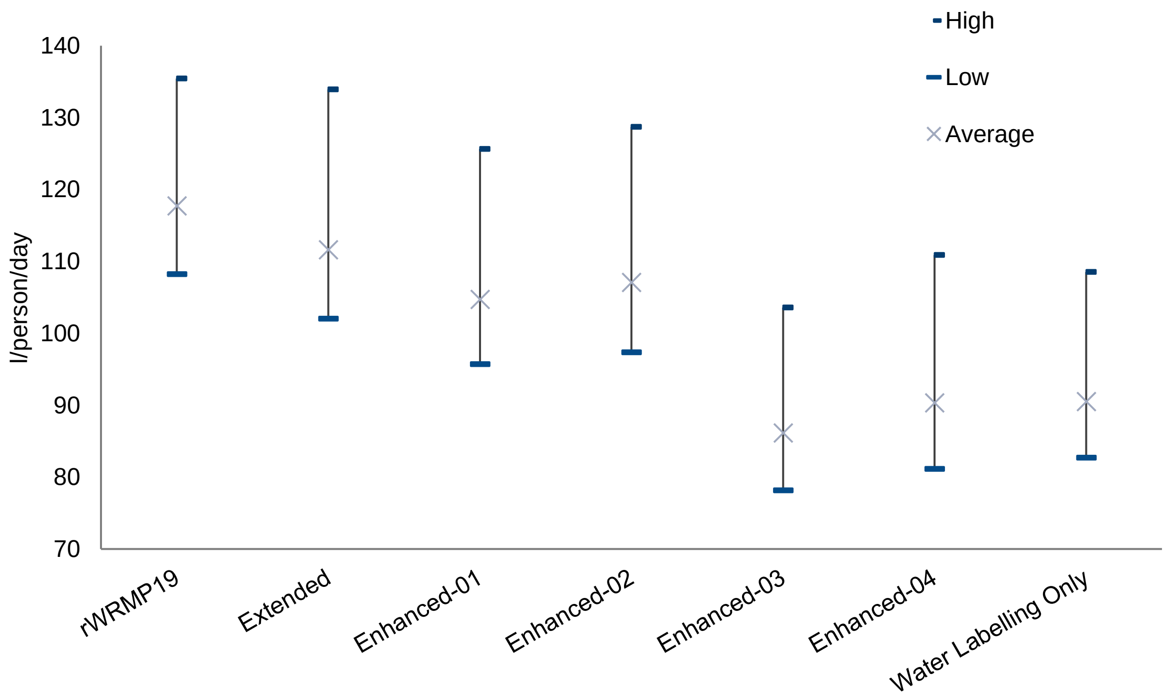


Figure 4: Uncertainty range around Water UK PCC scenarios in 2050



Three PCC scenarios were selected for this study based on the Water UK report. The high demand scenario PCC values derived by adjusting the PCC values in the revised draft WRMP (rdWRMP) so that an average PCC in 2050 was 127 l/person/day assuming high population growth. This scenario reflected the uncertainty around the delivery of the rdWRMP19 PCC values shown in figure 4. The central PCC scenario was taken directly from the rdWRMP19 tables.

The results from the WaterUK study suggested that the low demand scenario PCC of 110 l/person/day could be achieved by water company lead interventions. The scenario was developed by adjusting the Enhanced-02 water company profiles so that a national PCC of 110 l/person/day was obtained. The individual water company WRZ PCC values were then adjusted within the company to match the water company PCC. There was a check to see that the WRZ PCC in 2050 was within 10 l/person/day of the company average PCC.

The time profile of the national PCC for the three scenarios used can be seen in figure 5. The range of PCC across the regions in 2050 for the three scenarios can be seen in figure 6.

Figure 5: The change in PCC between 2025 and 2050 for the high, central and low scenarios

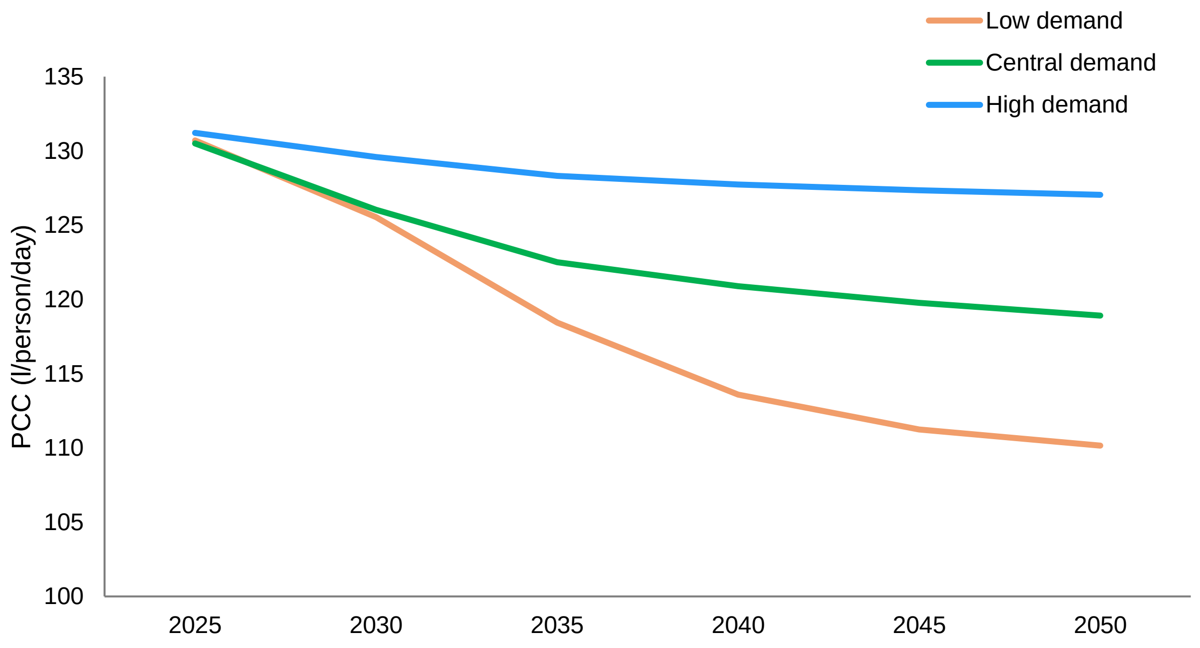
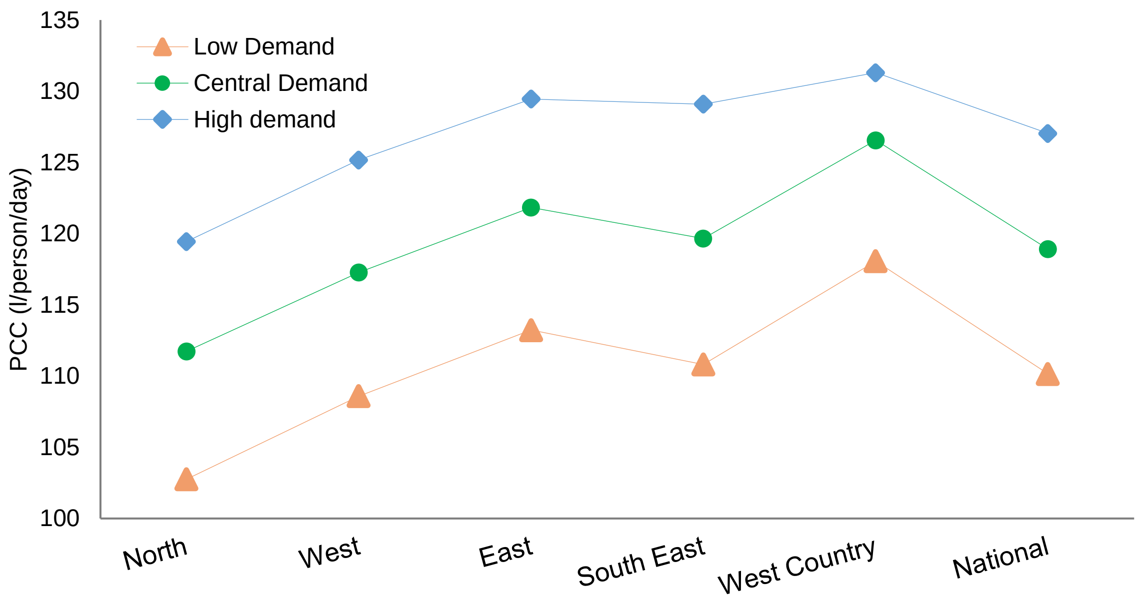


Figure 6: Regional PCC values in 2050 for the high, central and low demand scenarios

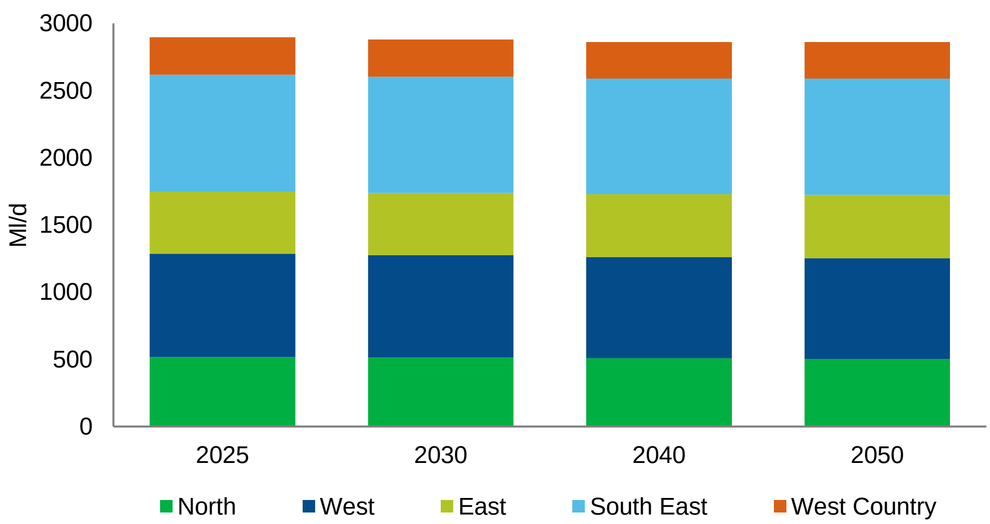


2.5. Public water consumption

Water consumption is made up of household and non-household consumption. The national water resources supply demand model concentrated on adjusting the household demand by looking at the impact of different PCC on future demands in the regions.

However, just over 20% of the water put into supply by water companies is classed as non-household use. The non-household consumption was taken from the WRMP19 tables. The actual volumes only changed slightly during the simulation period (see figure 7).

Figure 7: Change in non-household demand by region between 2025 and 2050



Household consumption varied depending on the population and PCC scenario as shown in figure 8 below. For the “do-nothing” option climate change was assumed to have an impact on consumption of 1% over the twenty five years between 2025 and 2050, this was in line with the Water Resources Management Plan guidance.

Moving from a high population growth scenario to a central population growth scenario could reduce demand by around 450 Ml/d by 2050. Moving from a high population scenario to a low population scenario could reduce demand by around 840 Ml/d. In the south east the equivalent reductions were 130 Ml/d and 285 Ml/d (see table 5 below).

Figure 8: Total consumption for different scenarios in 2050 with different population growth projections

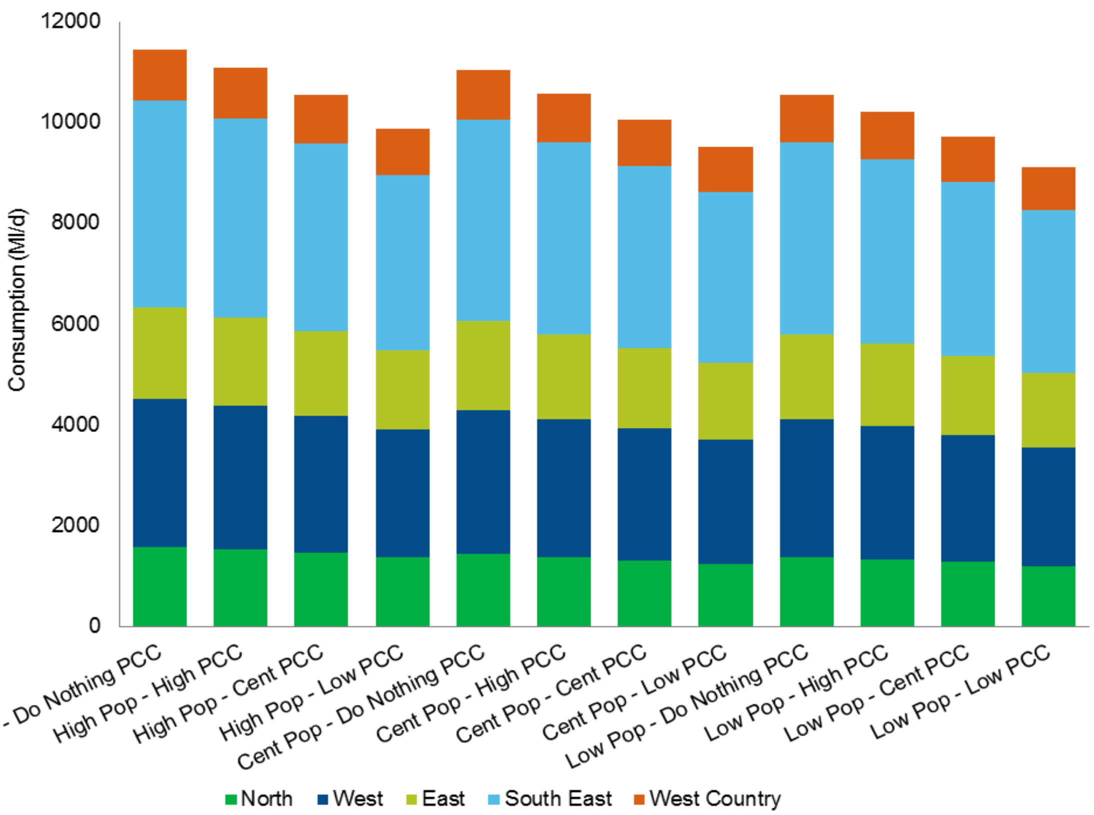


Table 5: Impact on consumption in 2050 of moving from a high population growth assumption to a central or low population growth scenario

Region	Move from High to Central Population Growth				Move from High to Low Population Growth			
	Do Nothing PCC	High PCC	Central PCC	Low PCC	Do Nothing PCC	High PCC	Central PCC	Low PCC
North	-138.5	-152.9	-150.6	-127.7	-198.7	-194.3	-188.2	-177.2
West	-84.3	-110.4	-105.2	-70.0	-214.4	-204.8	-191.7	-178.0
East	-45.9	-63.0	-60.4	-38.5	-119.2	-114.3	-107.6	-100.0
South East	-125.2	-153.6	-144.9	-102.2	-315.3	-299.8	-277.9	-257.3
West Country	-23.5	-33.7	-32.8	-20.5	-62.5	-60.7	-58.5	-54.6
Total	-417.4	-513.6	-493.9	-358.8	-910.1	-873.9	-823.9	-767.1

2.6. Impact of sustainability changes on public water supply

Sustainable abstraction is essential to ensure that river flows and groundwater levels support ecology and natural resilience. There are a significant number of locations were abstractions are potentially unsustainable.

A changing climate is likely to bring greater variability in rainfall and higher temperatures which could lead to different environmental water needs in the future to protect the environment. Moving to sustainable abstractions will provide greater resilience to changes in climate and drought pressures. The potential longer term changes needed to address unsustainable abstraction are covered further in the main report (section 5.4) and Appendix 4.

The sustainability change dataset used in the national water resources supply demand model has been generated using the rdWRMPs to understand what sustainability reductions have resulted from the Water Industry National Environment Programme (WINEP). This included confirmed sustainability reductions and any additional sustainability reductions water companies have tested in scenarios.

We have produced three scenarios (lower, middle and upper) of sustainability changes on public water supplies from the data in rdWRMPs. We have used the upper of these in our estimation of pressures on public water supplies as it best represents the long term direction of travel.

The lower scenario is taken from the water company planning tables. These are sustainability reductions the water companies have committed to making and are comprised primarily of the green and amber WINEP schemes. Green schemes are certain to go ahead because investigations and options appraisal has been completed and solutions are cost beneficial and affordable. Amber schemes are indicative only at this stage, and are where a likely change required may be waiting assessments on affordability or completion of an investigation. The total abstraction reduction in this scenario is 250 Ml/d.

The middle scenario includes all the reductions from the lower scenario and changes included within WRMPs where water companies have tested further sustainability reductions via scenario analysis. Where companies have presented more than one scenario we have selected the largest reduction or earliest implementation time. Generally these water company scenarios contain the green, amber plus the red WINEP schemes, which are those where there is evidence that action is required however the exact solution or change is not yet clear and so the changes are indicative or unconfirmed. The total change in this scenario is 523 Ml/d.

The upper scenario includes all the changes in the middle scenario and plus an indication of the direction of travel. Four water companies provided a further scenario which looked at estimated further sustainability changes that may be required following further investigation or future legislation or requirement changes. Examples include changes to abstraction to protect chalk streams, meet protected area revised Common Standards Monitoring Guidance requirements for flow and changes to prevent deterioration of water body status (where investigations are proposed for 2020 to 2025). The details of the action required in this scenario are less clear but it represents the changes likely to be required in the long term. The total change in this scenario is 720 Ml/d, beyond the sustainability reductions already planned up to 2025.

We have used the upper scenario in the modelling for the national framework as this is in line with our high ambition for environmental improvement, and represents the likely changes needed in the long term.

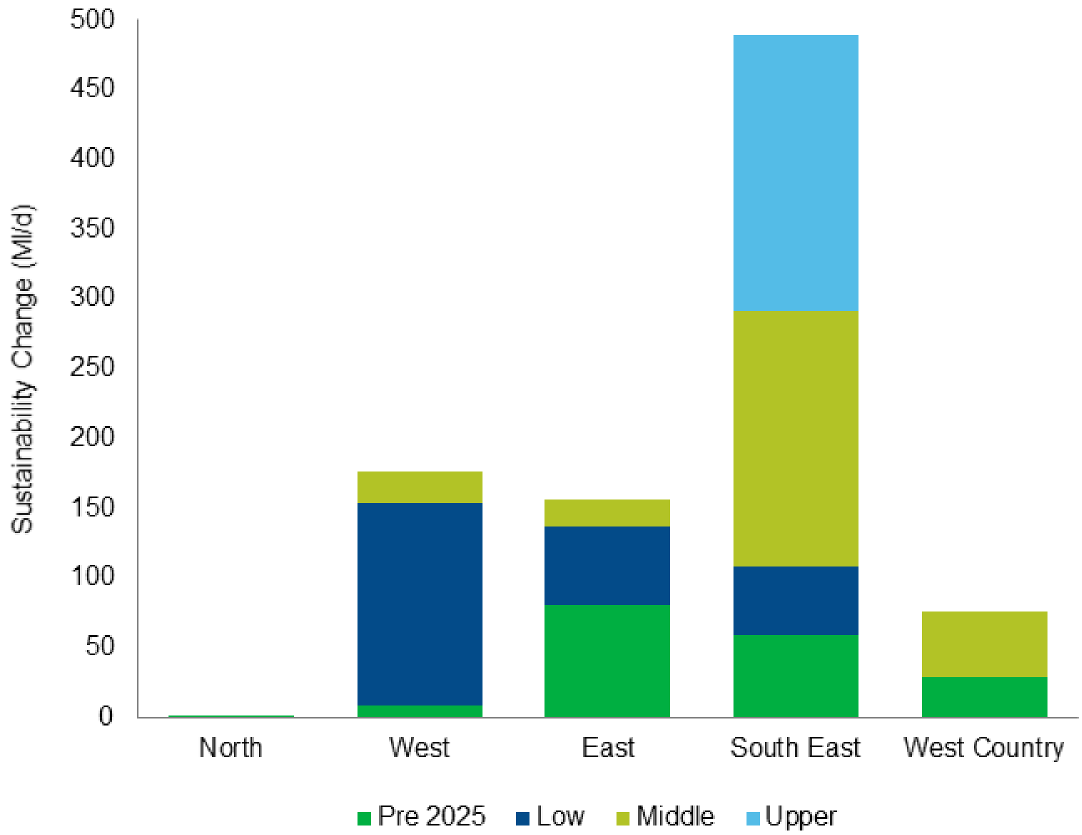
Our modelling starts from 2025 and some sustainability reductions have been included in company plans before this date. These amount to 183 Ml/d of confirmed sustainability reductions.

The sustainability reductions for each scenario have been estimated at the WRZ level. The regional values for each scenario and the values for sustainability reductions planned between 2020 and 2025 are shown in table 6 and presented graphically in figure 9 for comparison. Because our analysis of water needs starts at 2025, sustainability changes made before 2025 are excluded from the modelling.

Table 6: Regional group sustainability reductions summary. All volumes given in the three scenarios are for 2045 and totals should be considered cumulatively. The data has been taken from the revised WRMP tables and was sent to water companies in July 2019 to review, there may be slight changes in the final WRMP as sustainability reductions are continually reviewed with the Environment Agency.

Regional Group	Pre 2025 (Ml/d)	Lower scenario (Ml/d)	Middle scenario (Ml/d)	Upper scenario (Ml/d)
Water Resources North	1.50	0.00	0.00	0.00
Water Resources West	9.00	144.60	23.10	0.00
Water Resources East	85.22	56.34	19.13	0.00
Water Resources South East	58.21	49.29	184.01	198.12
West Country Water Resources	28.81	0.00	47.01	0.00
Total	182.74	250.23	273.25	198.12

Figure 9: Regional break down of sustainability reductions post 2025 and under each scenario: lower, middle and upper



2.7. Climate change impact on public water supply availability

England's climate is changing and will continue to change as a result of greenhouse gas emissions. Climate change means that droughts are also becoming more frequent and this needs to be incorporated into plans to increase the level of public water supply resilience to drought. Adapting to climate change early also means an increase in resilience to more extreme drought.

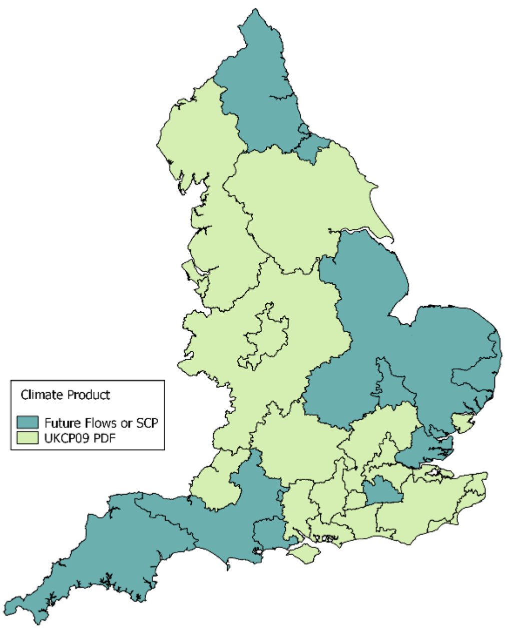
There is a large amount of the uncertainty around the prediction of future climate change impacts on public water supplies. This can be seen by the large allowance for climate change uncertainty in water company WRMP19 plans. Sources of uncertainties include; variations in results from different climate change models, the choice of greenhouse gas emission scenario, impact of changing climate seasonal patterns (e.g. drier autumns) and the time period of impact (e.g. 2080 predictions show an accelerated impact).

Our assessment of climate risks in the national water resource supply-demand model was taken from the water company WRMP19 tables and gives a single prediction for the potential impact of climate change. This does not fully represent the uncertainty around future predictions. As more modelling is undertaken, such as the outputs from UKCP18 and the work undertaken by the University of Oxford (see section 4), a better understanding of the impact of these uncertainties on future public water supplies will emerge.

In water company water resources management plans 2019, the impact of climate change on water sources was based on UKCP09 data, with most water companies using the UKCP09 medium emissions scenario. UKCP09 climate projections generally indicate wetter, milder winters, a shorter sharper groundwater recharge season, higher temperatures, increases in potential increased evaporation and drier soils. During extended drought periods the wetter winters would not offset the impact of dryer summers.

The water company water resources plans 2019 guidance included a tiered approach to assessing climate change impacts. For high vulnerability WRZs, the guidance suggested the use of probabilistic projections to give a more comprehensive representation of uncertainty. For WRZ with medium or low vulnerability the Spatially Coherent Projections[2] or Future Flows[3] could be used. This variety in approach means the results are not strictly comparable between companies. Figure 10 indicates the approach used in each WRZ.

Figure 10: Datasets used for WRZs in England for WRMP19



The Water Resource Planning guidance for the 2019 plans required water companies to quantify the impact of climate change on water availability that has occurred since the 1990s and incorporate this impact into the first 5 years of their plans. Water companies also had to include an adjustment to cover the uncertainty associated with climate change. Figures 11a and 11b show how these two components of climate change impact over the period 2020 to 2050 with a split to show the impact pre and post 2025. While the uncertainty around climate change impacts increases over the WRMP19 forecast period, the amount of climate change 'headroom' that companies plan to maintain in their plans reduces over time. This is because they accept a higher level of risk further into the future as there should be time to adapt. The result of this approach means that companies plan to accommodate almost all of the uncertainty created by climate change in the pre-2025 values, but in the longer term they leave more of that uncertainty unresolved as they accept increasing levels of long term risk. Figure 11b plots the climate change impact by region based on water resource management plan data.

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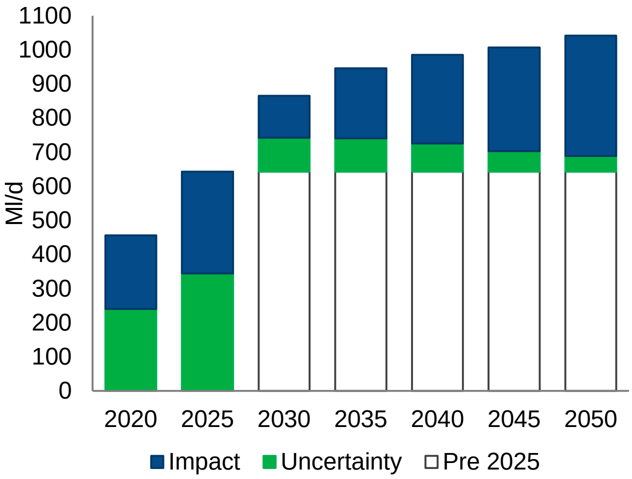
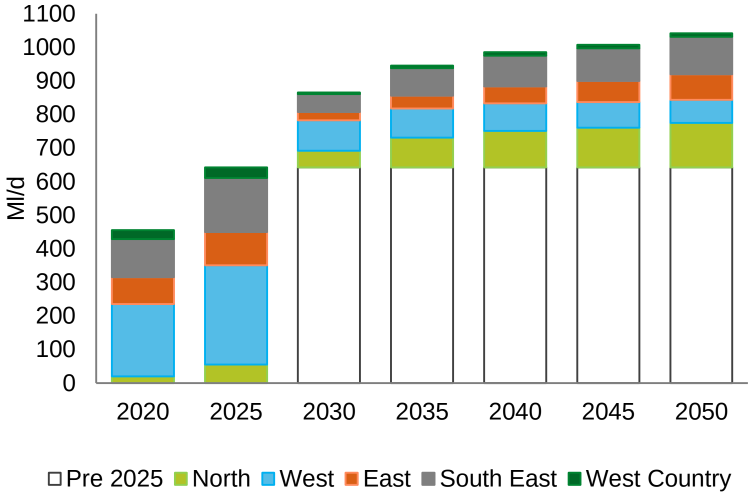
[2] Sexton, D. M. H, Harris, G. and Murphy, J. (2010) UKCP09: Spatially coherent projections. UKCP09 additional product. Available from: http://cedadocs.ceda.ac.uk/1336/1/tech_note_of_spatially_coherent_projections.pdf accessed on 5th December 2019

[3] C. Prudhomme, T. Haxton, S. Crooks, C. Jackson, A. Barkwith, J. Williamson, J. Kelvin, J. Mackay, L. Wang, A. Young, and G. Watts (2012) Future Flows Hydrology: an ensemble of daily river flow and monthly groundwater levels for use for climate change impact assessment across Great Britain

Figures 11a and 11b: WRMP19 reduction in water available between 2020 and 2050 due to climate change by a) component, and b) by region (The 'uncertainty' around climate change is how much of that total climate change uncertainty the company is looking to offset in its long term plan, while accepting increasing levels of risk into the future)





The water company WRMP19 data suggests that between 2025 and 2050 around 80% of the existing water available in 2025 would be impacted by future climate change and more than 50% of the existing water availability would see a 5% or greater reduction.

The Water Resources Planning guidance allowed water companies to make an allowance for the impact of climate change on water demand. The assumption for the modelling was that there was an impact of around 1% over the twenty five years between 2025 and 2050, this is in line with the water resources management plan guidance. The impact of climate change on demand was added as part of the "do-nothing" scenarios leading to an increase in per capita consumption over the modelling period for those scenarios.

2.8. Public water supply resilience data

Using the data provided by the water companies in WRMP19 table 10 it was possible to estimate the impact of having no demand side or supply side drought measures for different drought scenarios provided by the water companies at a WRZ scale. Nearly all water companies provided drought scenarios for 1:200 and 1:500 drought events. To obtain a consistent estimate of water availability and demand it was necessary to check and remove the impact of the drought options.

Figure 12 shows an estimate of the volume of water needed for each region to increase drought resilience from the current level to a 1 in 200 and 1 in 500 level. The south east has the largest change requirement to achieve a 1:500 resilience.

Figure 12: Additional water required to increase drought resilience to 1:200 and 1:500 by region

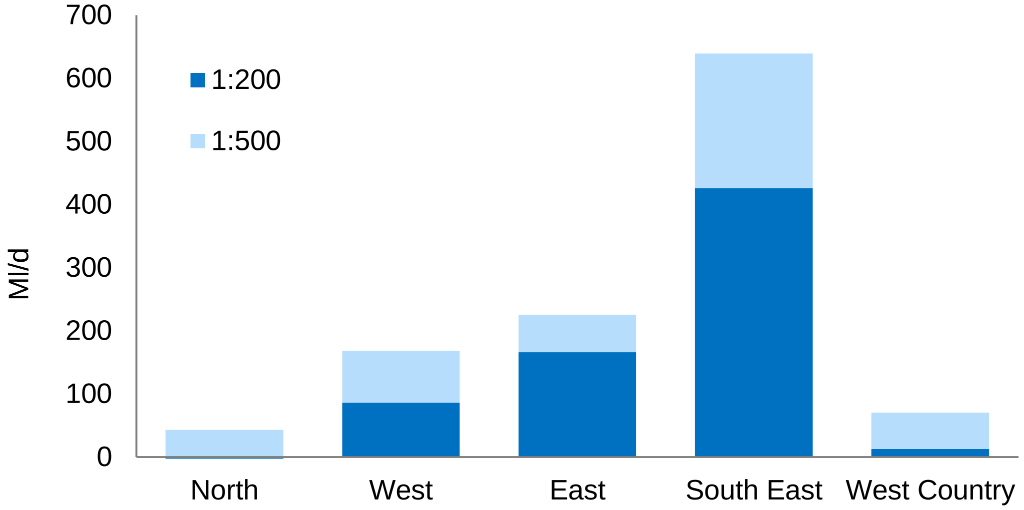
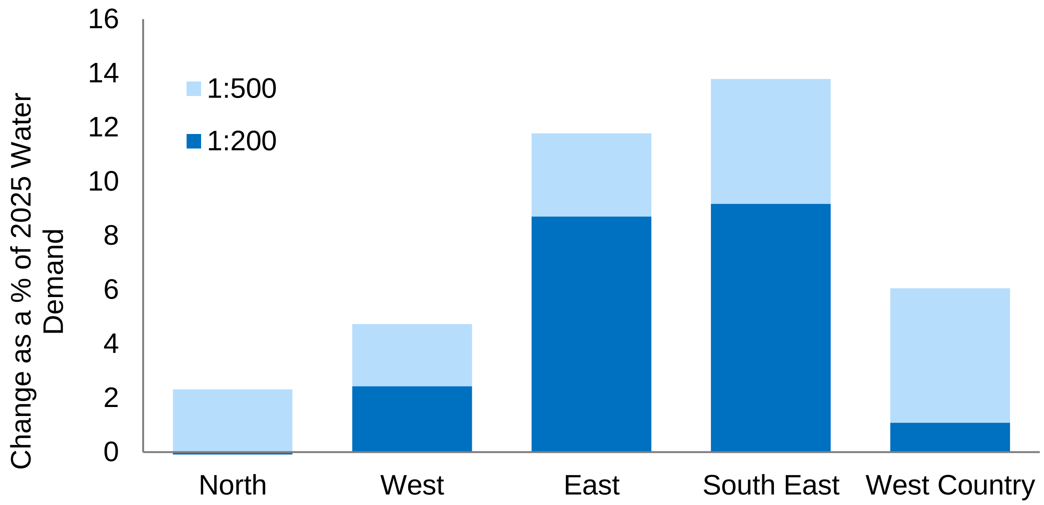


Figure 13 shows an estimate of the volume of water needed for each region to increase drought resilience from the current level to a 1 in 200 and 1 in 500 level as a % of the regional dry year public water demand in 2025. Again the south east has the largest % change, with the east also showing a large % change.

Figure 13: Additional water available required to increase drought resilience to 1:200 and 1:500 by region as a % of dry year public water demand in 2025.



2.9. Drought measures

As part of the National Water Resources Long-Term Planning Framework[4] water company drought plans were reviewed to identify the location, estimated frequency of use, nature (e.g. winter/summer) and level of environmental sensitivity of the key drought permits and orders that might be used by water companies during the lead-in to a severe drought. Each drought permit or order included in company drought plans was categorised as

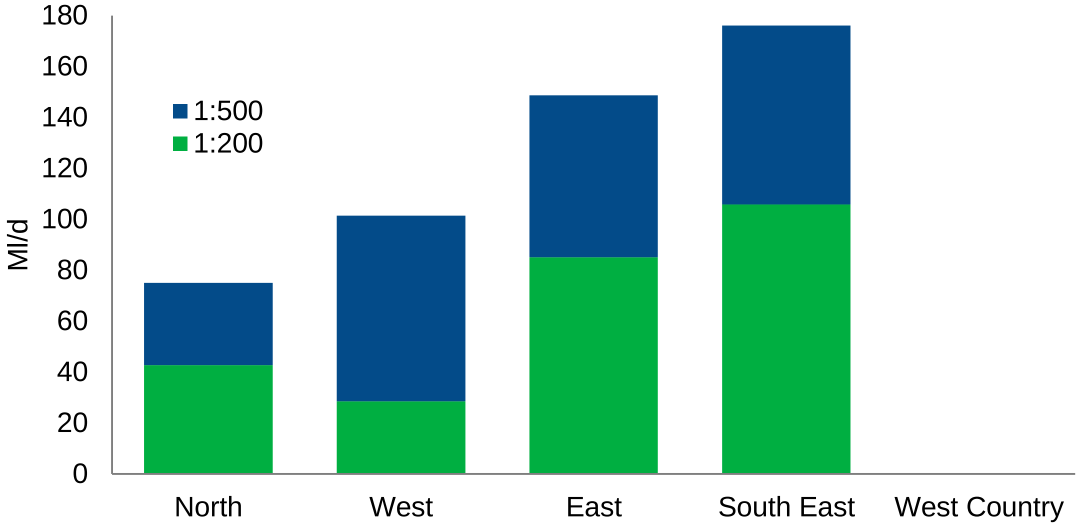
[4] National Water Resources Long-Term Planning Framework , Water UK (2016)

‘likely’, ‘possible’ or ‘unlikely’ depending on the stated level of environmental risk, priority for implementation and the severity of the drought situation. By referencing back to water company drought plans and the information in the WRMP19 Table 10 it was possible to allocate the drought permits and orders volumetric values to individual WRZ.

The water available from drought permits and orders depended upon the likelihood of the drought event. For a 1 in 200 event it was assumed that all the likely drought permits and orders plus 50% of the possible drought permits and orders would be available. During a 1:500 event it was assumed that all the likely and possible drought permits would be available. To reflect the uncertainty around the availability of drought permits and orders during low frequency drought events the water available was reduced by 30%.

Figure 14 shows the assumed water available from drought permits and orders for each region. No drought permits or orders were identified for the West Country. The estimated water available from all drought permits and orders across England was around 1158 Ml/d, of this 116 Ml/d were categorised as likely to be available, 683 Ml/d as possibly available and 359 Ml/d as unlikely to be available. For the modelling undertaken it was assumed that for a severe drought event the water available from drought permits and orders was 262 Ml/d. During an extreme drought event the water available was assumed to be 501 Ml/d.

Figure 14: Assumed water available benefit of drought permits/orders by region and drought likelihood



Temporary use bans (TUBs), historically referred to as hosepipe bans, are an established way for water companies to reduce demand in times of drought. The Environment Agency requires water companies to implement TUBs before drought permits and orders are granted, particularly in summer or hot, dry periods. This requirement can be relaxed during winter periods when TUBs can have a lesser impact.

An UKWIR[5] report published in 2007 identified summer reductions in the order of 5% for a ban on unattended hosepipes and sprinklers, 5 - 9.5% for a full hosepipe ban, and 18.5% for a non-essential use ban. A review undertaken by Water Resources South East suggested that in the south east of England the implementation of TUBs would typically

[5] UKWIR Report Ref No: 07/WR/02/3

result, on average, in a reduction of between approximately 3% and 5% of demand during a hot dry summer.

The national water resources supply demand model has assumed that during a 1:500 drought event that TUBs would be in place. The level of demand reduction was assumed to be a 2% reduction in the dry weather annual household demand.

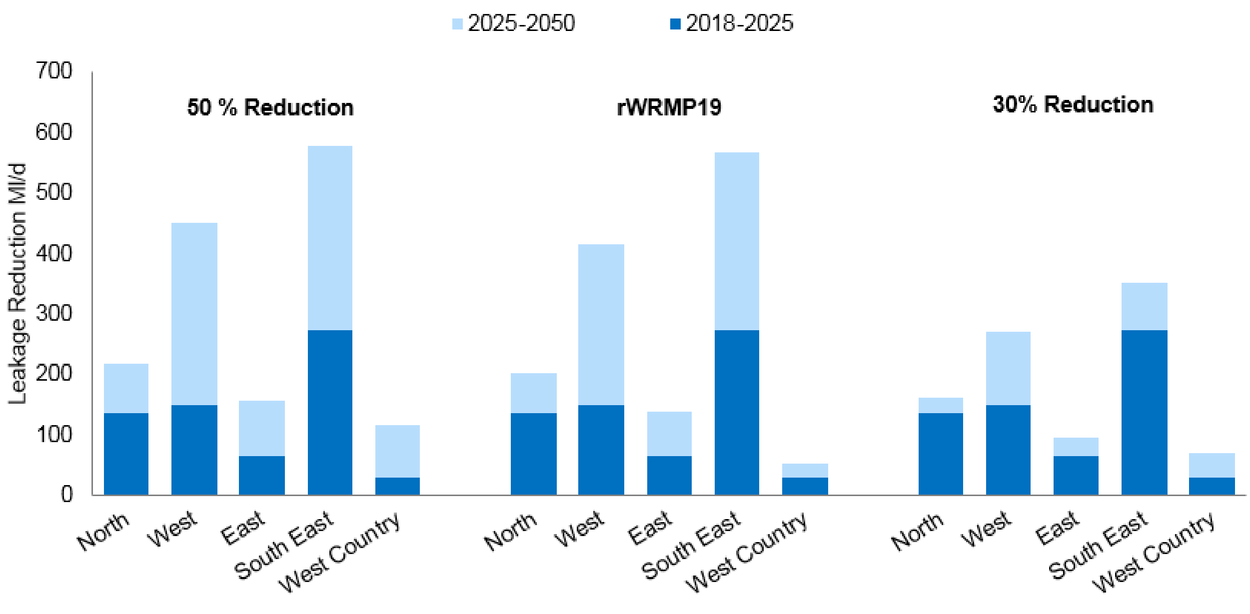
2.10. Leakage

Three leakage scenarios have been used. These are a 50% reduction in leakage from 2017/18, 30% reduction in leakage from 2017/18 and the leakage reductions in the water company rdWRMP19. The % reduction leakage values were generated by assuming a linear reduction from the rdWRMP19 values in 2025 to the 30% and 50% leakage values required by 2050.

Total leakage in England in 2017/18 from the WRMP19 Tables was 3034 Ml/d, a 50% reduction is 1517 Ml/d and a 30% reduction is 910 Ml/d. The rdWRMP19 leakage reduction by 2050 was estimated as 1422 Ml/d. Since the rdWRMP19 were produced all water companies wholly or mainly in England have committed to achieving the 50% reduction in 2017/18 leakage levels by 2050.

The start year for the modelling was 2025 so the actual reduction in leakage between 2025 and 2050 depended upon the planned leakage reduction between 2020 and 2025. As can be seen from figure 15 below the proportion of leakage reductions pre 2025 varied across the regions. The North had the highest proportion leakage reduction pre 2025 and the West Country the lowest.

Figure 15: Pre and post 2025 leakage reductions

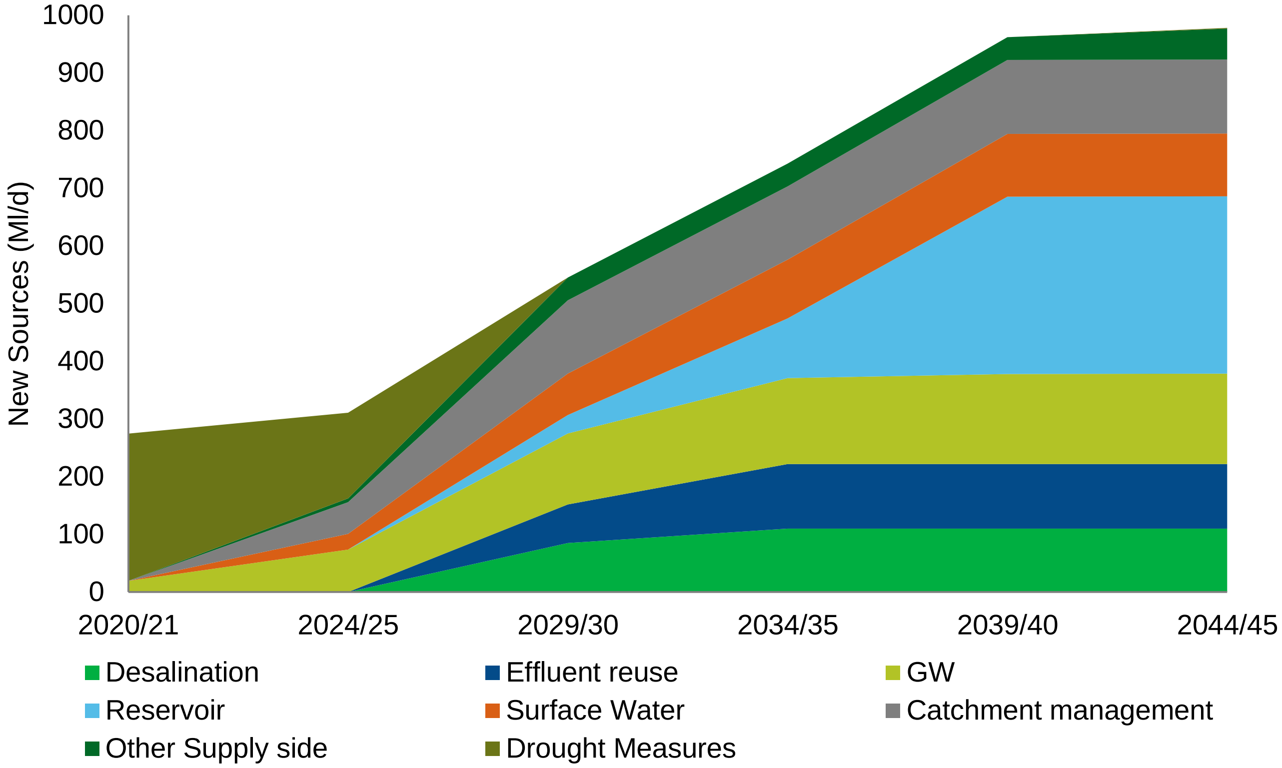


2.11. Water Company preferred options to increase supply and transfers

By comparing the change in the final plan total water available for use between 2025 and 2050 (after adjusting for any changes in baseline transfer values) the increase in supply and transfers can be calculated for each WRZ. The WRZ values were used to calculate the regional increase in supply and transfers between 2025 and 2050. The values were then checked against the preferred supply option in the water company water resources management plans. The water companies also identified other feasible supply side options that they did not select.

Figure 16 below shows the makeup of the preferred new supply options (i.e. excluding transfers) in the water company plans between 2020 and 2050. Options that are quicker to implement, such as drought measures and ground water options, appear early in the timeline, then desalination, effluent reuse and surface water options and later in the planning period reservoir developments.

Figure 16: New WRMP19 preferred new source option type between 2020 and 2045



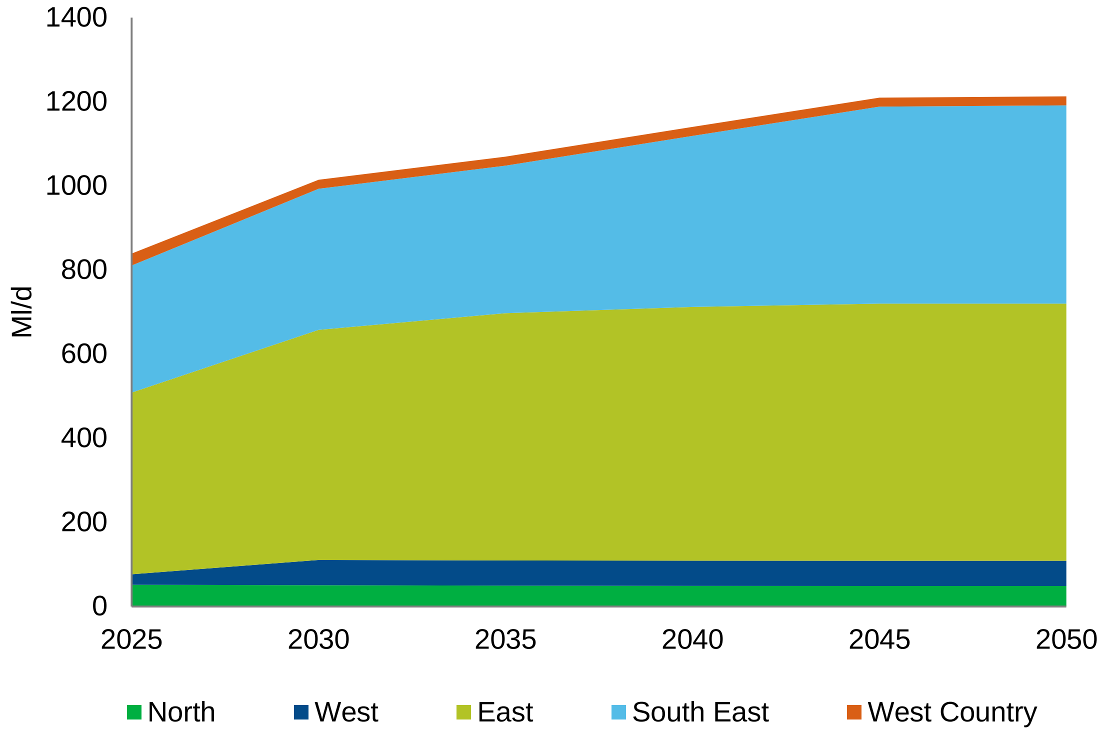
In 2025 nearly 50% of the preferred options are drought measures such as demand restrictions and drought permits. By 2030 the use of drought measures has been reduced significantly. The drought measures were not included in the modelled supply side options.

All the catchment management schemes have been identified by Southern Water. These were the preferred solution to the reduction in water availability due to diffuse pollution such as agricultural run-off affecting sources. Southern Water have developed a series of catchment management schemes to mitigate against these diffuse sources of pollution.

Between 2025 and 2045 the South East has seen the biggest increase in new supply options (around 670 Ml/d). The West also sees a large increase in new supply sources (213 Ml/d). The North and South West have only very small new sources developments. The East has around 55 Ml/d of new supply development, with transfer options moving surplus water freed up by demand side options.

In their WRMP19 water companies are also planning to increase transfers between WRZ. The planned change in WRZ water imports between 2025 and 2050 is shown in figure 17. Overall there is a planned increase in WRZ imports of 374 Ml/d. Most of the increase in WRZ imports occurs in the East (180 Ml/d) and South East (170 Ml/d),

Figure 17: Change in WRZ imports



2.12. Pre 2025 and post 2050 analysis

The prime focus of the national water resources supply demand model was on the period 2025 to 2050. This was based on the assumption that water companies would have delivered the first 5 years of their WRMP19 plans.

Water companies' plans address some significant supply and demand challenges during the 2020-2025 period. These include; population growth of around 1.6 million leading to an increase in consumption without action of around 180 Ml/d, sustainability reductions of around 180 Ml/d and around 640 Ml/d reduction in water available due to the impact of climate change. These challenges have been addressed by companies' plans to reduce leakage by 565 Ml/d, reduce average PCC to save around 326 Ml/d and to develop new sources of around 145 Ml/d by 2025. There are also plans to increase the amount of water being transferred between WRZ up from around 564 Ml/d in 2020 to 839 Ml/d by 2025. In a number of WRZ companies still plan to depend on drought measures such as drought permits and orders.

Overall, the pressures on supply and demand between 2020 and 2025 have been matched by the plans water companies have put in place. More details of the various pressures and plans are given below

Population and PCC

The modelled changes in population between 2020 and 2025 are shown in table 7. The predicted population growth of around 1.6 million is based on the high population growth scenario outlined in section 2.3. The table also shows the predicted decrease in PCC between 2020 and 2025, from an average of 138 l/head/d to 131.6 l/head/day. The biggest decreases in PCC are in the South East.

Table 7: Changes in total and household population and per capita consumption between 2020 and 2025

Region	Total population '000s			Household population '000s			PCC (l/h/d)		
	2020	2025	change	2020	2025	change	2020	2025	change
North	8006	8146	140	7887	8021	133	129	124	-5
West	15660	16024	365	14611	14951	340	133	130	-3
East	8428	8706	279	8292	8569	276	141	134	-7
South East	20403	21072	669	20122	20780	657	144	135	-9
West Country	4841	4988	148	4666	4811	146	139	134	-5
Total	57337	58937	1600	55578	57131	1553	138	132	-6

Consumption

Details of household and non-household consumption are given in table 8. Between 2020 and 2025 non-household water use is expected to reduce by about 37 Ml/d. If PCC remains at 2020 levels population increase would lead to a 216 Ml/d increase in household consumption. With the planned changes to PCC between 2020 and 2025 household consumption reduces by around 216 Ml/d. Combining non-household and household consumption total consumption reduces by 185 Ml/d from 10,502 Ml/d to 10317 Ml/d between 2020 and 2025.

Table 8: Changes in non-household and household consumption with and without changes in PCC between 2020 and 2025

Region	Non-household consumption (Ml/d)			Household consumption (Ml/d) with 2020 PCC			2025 Household consumption (Ml/d)		
	2020	2025	change	2020	2025	change	2020	2025	change
North	420	417	-3	1016	1033	17	1016	994	-22
West	769	768	-2	1943	1988	45	1943	1939	-4
East	464	463	-1	1168	1207	39	1168	1147	-21
South East	896	869	-26	2891	2985	94	2891	2795	-96
West Country	286	281	-5	650	670	20	650	645	-5
Total	2835	2797	-38	7667	7883	216	7667	7520	-148

Changes to water available

Water available is expected to reduce by 2025 due to the impact of sustainability changes, climate change, and other changes (mainly due to impact of groundwater pollution in the south east). The regional changes to water available between 2020 and 2025 are given in table 9. As part of WRMP19 water companies had to include the impact of climate change on water availability since the 1990s into the first five years of their plans. Combining this with the large uncertainty around the climate change predictions means that climate change has a significant impact on water availability in WRMP19 between 2020 and 2025.

Table 9: Changes in water availability in WRMP19 due to sustainability reductions, climate change and other factors between 2020 and 2025.

Region	Sustainability changes (Ml/d)		Climate change impact by 2025 (Ml/d)			Other changes (Ml/d)	
	2020	2025	Predicted	Uncertainty	Total	2020	2025
North	0	-2	-29	-26	-55	0	0
West	0	-9	-118	-178	-296	0	0
East	0	-81	-62	-36	-99	0	0
South East	0	-58	-72	-89	-161	0	-54
West Country	0	-29	-17	-15	-32	0	0
Total	0	-178	-298	-345	-643	0	-54

Leakage

Water companies have planned to make significant reductions in leakage between 2020 and 2025, with most companies aiming to achieve a 15% reduction in their WRMP19. Table 10 gives the regional breakdown of the proposed WRMP19 changes in leakage levels.

Table 10: Changes in the WRMP19 planned regional leakage between 2020 and 2025

Region	Leakage (Ml/d)			
	2020	2025	change	% Change
North	430	297	-133	-31%
West	897	753	-144	-16%
East	301	248	-54	-18%
South East	1079	877	-202	-19%
West Country	236	203	-33	-14%
Total	2943	2378	-565	-19%

New sources of water and WRZ imports

Water companies are planning to develop around 162 Ml/d of new sources of water during the period 2020 to 2025 as outlined in table 11. Most of the 68 Ml/d of new groundwater sources planned in WRMP19 for the south east offset the 54 Ml/d reduction in water availability shown in table 13 (other), which is associated with nitrate contamination issues in the region.

Table 11: New sources of water planned in WRMP19, by type and region, between 2020 and 2025

Region	New sources of water 2020-2025					
	Ground Water	Surface Water	Catchment	Production	Total	Drought Measures
North	2	0	0	6	8	0
West	0	26	0	0	26	0
East	4	0	0	0	4	0
South East	68	1	55	1	125	149
West Country	0	0	0	0	0	0
Total	74	27	55	7	162	149

There are plans to significantly increase transfers between WRZ in the period 2020 to 2025 with water imports into WRZ increasing from 564 Ml/d to 839 Ml/d. The regional changes in WRZ imports are detailed in Table 12.

Table 12: Change in WRZ imports, by region, between 2020 and 2025

Region	WRZ imports (Ml/d)		
	2020	2025	change
North	52	51	0
West	25	25	0
East	302	432	130
South East	157	302	145
West Country	28	28	0
Total	564	839	275

Overall Balance

A summary of the reductions in water availability across the regions during 2020 to 2025 is given in table 13. Overall there is a reduction of around 1053 Ml/d.

Table 13: Factors reducing water availability between 2020 and 2025, by region (Ml/d)

Region	Con-sumption (Ml/d)	Sustain-ability changes (Ml/d)	Climate change (Ml/d)	Other changes (Ml/d)	Total reduction (Ml/d)
North	-14	-2	-55	0	-70
West	-43	-9	-296	0	-348
East	-38	-81	-99	0	-218
South East	-68	-58	-161	-54	-342
West Country	-15	-29	-32	0	-76
Total	-178	-178	-643	-54	-1053

Between 2020 and 2025 there is an increase in water available of around 1040 Ml/d due to water efficiency, leakage reduction and new sources (see table 14). Matched against the reductions outlined in table 13 there is an overall reduction in water available of around 14 Ml/d.

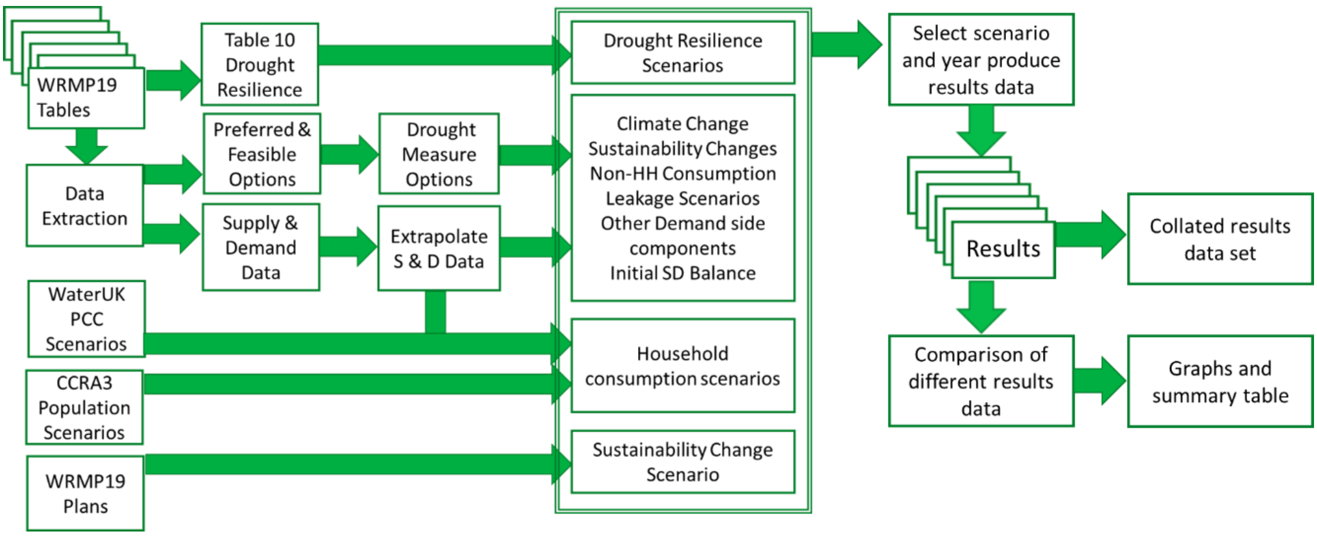
Table 14: Factors increasing water availability between 2020 and 2025, by region, and comparison with reductions in water available

Region	Water efficiency (Ml/d)	Leakage (Ml/d)	New sources (Ml/d)	Total increase (Ml/d)	Total reduction (Ml/d)	Change (Ml/d)
North	36	133	0	169	-70	98
West	47	144	0	191	-348	-157
East	59	54	0	113	-218	-105
South East	164	202	149	514	-342	172
West Country	20	33	0	53	-76	-23
Total	326	565	149	1040	-1053	-14

2.13. Modelling approach

The approach used in the national water resources supply demand model is outlined in figure 18. This involved three stages, collating the input data, selecting the scenario and comparing the scenario results. All the analysis was done using excel spreadsheets.

Figure 18: EA national water resources supply demand model approach



The collation of the data has been outlined in the previous sections. The individual data sets were linked to the analysis spreadsheet.

The spreadsheet calculated the water available and demand in each WRZ for a defined year with a defined scenario (e.g. population growth and water efficiency). Scenario selection is covered more in the next section.

The outputs for each model run were collated and compared. For example, the scenario results for a particular year were compared with the 2025 base year run results to identify the scale of change.

2.14. Modelling scenarios

The national water resource supply demand model used a spreadsheet to calculate the impact on water availability and water demand for public water supply in each WRZ in England under a number of different scenarios. The analysis was based on the information from the water companies rdWRMP19 data. This data was adjusted to match the scenario conditions.

The scenario could vary components such as; the annual likelihood of level 4 drought restrictions, level of sustainability restrictions, rate of population growth, household per capita consumption, non- household water efficiency, leakage reduction, water saving from demand side drought restriction and use of drought permits and drought orders. More details of the scenario options are given in table 15.

Table 15: Scenario Options by component

Component	Scenario Options			
Resilience	Current	1:200	1:500	
Population Growth	High	Central	Low	
Climate Change	None	WRMP19		
Sustainability	WRMP19	+Extended	+Additional	
New Supply Sources	None	WRMP19		
2050 Household PCC (l/h/d)*	135	127	119	110
2050 Non-Household reduction	0%	2%	4%	
Leakage by 2050	Current	30%	WRMP19	50%
Demand Side Drought Actions	0%	2%	4%	
Supply Side Drought Actions	100%	70%	50%	
***Additional PCC Scenarios for 113, 108, 106, 95, 92 and 87 l/h/d based on the scenarios developed by Water UK study described in section 2.4**				

Five Scenarios were run, two baseline and three future scenarios. The baseline scenarios simulated the water situation in 2025, while the “do nothing” options predicted the water situation in 2050 if no new options were implemented either to reduce consumption or leakage or to increase supply through developing new options. Details of the scenarios are given in table 16.

Table 16: Modelling scenarios

	Base line	Do nothing	Best case	Central case	Worst case
Year	2025	2050	2050	2050	2050
Resilience	Current	1:500	1:500	1:500	1:500
Population Growth	High	High	High	High	High
Climate Change	WRMP19	WRMP19	WRMP19	WRMP19	WRMP19
Sustainability	+additional	+additional	+additional	+additional	+additional
New Supply Sources	None	None	WRMP19	WRMP19	WRMP19
Household PCC (by 2050)	132 l/h/d	132 l/h/d	110 l/h/d	118 l/h/d	127 l/h/d
Non-Household reduction by 2050	0%	0%	4%	0%	0%
Leakage reduction (from 2017/18)	As in 2025	As in 2025	50 %	WRMP19	30 %
Demand Side Drought Actions	0%	0%	2% saving	2% saving	2% saving

An overall summary of the results from the five scenarios can be seen in table 17. It should be noted that the values between the baseline Water Available for Use (WAFU) and the final plan WAFU do not fully match up with the preferred options due to mismatches in the import and exports values reported by water companies. The overall decrease of water availability under the “do nothing” option of 3,435 Ml/d can be seen in the difference in the baseline 2025 scenario and the “do nothing” scenario. The other “difference” columns show the difference between the simulation scenario and the “do nothing” scenario.

Table 17 Summary results from scenario simulations

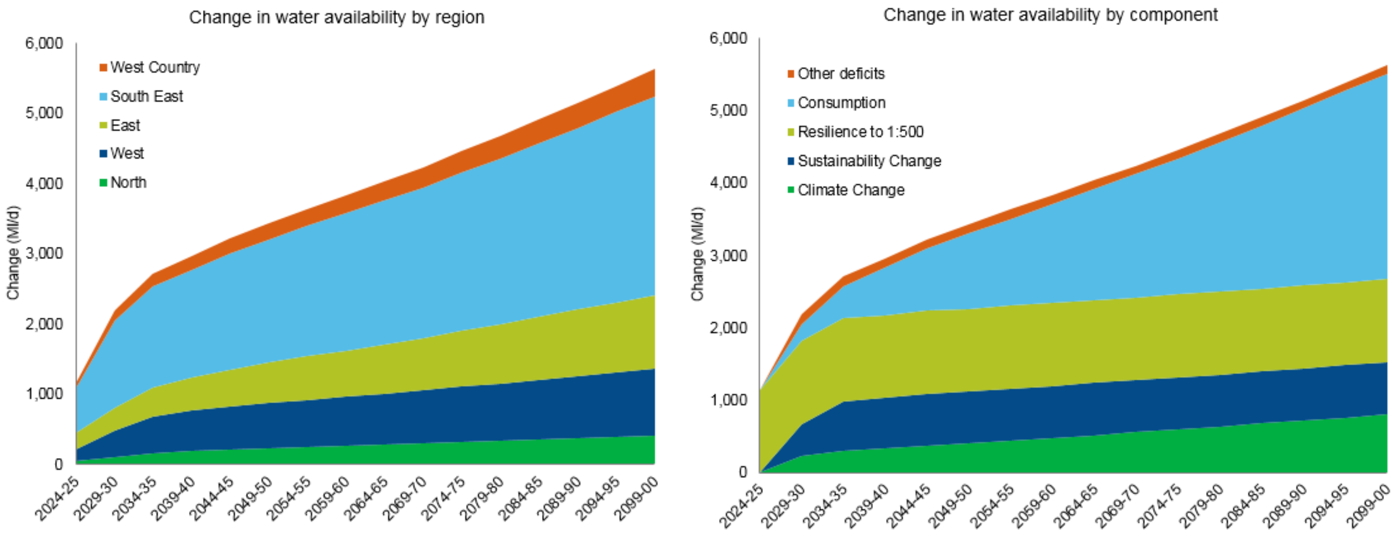
	Scenario (Ml/d)					**Difference (Ml/d)**			
	Base	Do N	Worst	Central	Best	Do N	Worst	Central	Best
Year	2025	2050	2050	2050	2050				
HH consumption	7520	8593	8213	7687	7121	1074	-381	-906	-1472
non HH consumption	2897	2860	2860	2860	2746	-37	0	0	-114
Leakage	2378	2378	2083	1613	1515	0	-294	-765	-863
Operational losses	353	353	354	354	354	0	1	1	1
Distribution input	13147	14184	13510	12514	11735	1037	-674	-1670	-2449
Water available	16585	16585	16585	16585	16585	0	0	0	0
Resilience impact	0	-1145	-1145	-1145	-1145	-1145	0	0	0

	Scenario (Ml/d)					Difference (Ml/d)			
Climate change	-298	-651	-651	-651	-651	-353	0	0	0
Sustainability changes	-178	-900	-900	-900	-900	-722	0	0	0
Other changes	-54	-187	-187	-187	-187	-133	0	0	0
Water available	16055	13702	13702	13702	13702	-2353	0	0	0
Production use	321	321	304	304	304	0	-17	-17	-17
Outage allowance	709	709	705	705	705	0	-4	-4	-4
Baseline WAFU	15025	12672	12693	12693	12693	-2353	21	21	21
Baseline total WAFU	14989	12636	12615	12615	12615	-2353	-22	-22	-22
Production options	-5	-5	-20	-20	-20	0	-15	-15	-15
Resource options	145	145	958	958	958	0	813	813	813
Final plan WAFU	15165	12812	13631	13631	13631	-2353	819	819	819
Final plan total WAFU	15148	12795	13640	13640	13640	-2353	845	845	845
Headroom (climate c)	345	391	391	391	391	46	0	0	0
Headroom (all other)	647	647	623	623	623	0	-25	-25	-25
Available headroom	2000	-1389	131	1127	1905	-3389	1520	2516	3294
Surplus water	1008	-2427	-882	113	892	-3435	1544	2540	3319
HH PCC (l/head/day)	132	133	127	119	110	1	-6	-14	-23

2.15. Year 2100 deficit

The extended WRMP19 data set allowed the scale of future deficits to be predicted out to 2100 under the Do Nothing scenario. Figure 19 shows the change in water availability components by a) the components and b) by region. The estimated change in water availability of around 5635 Ml/d by 2100 is likely to underestimate the impact of climate change and sustainability reductions.

Figures 19a and 19b: Predicted reduction in water availability (Ml/d) out to 2100 under the do nothing scenario by a) component and b) region.



2.16. Modelling assumptions

The national water resources supply demand model has pulled together the WRZ information provided in water company WRMP19 plans and tables to provide a national and regional picture of the future challenges to public water supply. The results provide a reasonable approximation of the scale of the challenge but do not adequately represent the uncertainty around the results. The results support the outputs from previous studies but further work is required that will need more consistent data, models and approaches to be developed and used.

Collating the WRZ data from the WRMP19 tables has highlighted inconsistencies in how WRMP19 table data has been reported. Significant effort has been put into making the data as consistent as possible but differences in approaches around how the data was calculated and derived from supporting models still exists.

The use of an “aggregated” model that reports an annual average value for water availability under a specific type of drought event provides a single estimate of what the future supply/demand balance might look like during a theoretical ’design’ drought event at a given point in the future. This approach will not give the same level of understanding of the uncertainties around water availability and demand that would be obtained from a system simulation model using a nationally consistent library of drought events.

Many of the data inputs into the national water resource supply demand model also have significant levels of uncertainty. In particular this includes the future prediction of climate change impacts, sustainability reductions and population growth. Each of these components have a significant influence on future water availability and need.

There are uncertainties around the robustness, costing and environmental acceptability of the proposed options to manage future water availability shortfalls. These include;

- achieving and maintaining the planned level of reduction in leakage and water use,
- use and benefit of drought measures, and
- environmental impact of transfer schemes, new resources schemes, such as effluent reuse and desalination.

The underlying assumption that the same level of drought would be occurring at the same time in all of the WRZ is a simplification. The modelling undertaken by The University of

Oxford (see section 4) utilised a library of spatially coherent climate scenarios to better represent the natural variation in drought events across the country. In order to better understand the scale of the risk associated with climate change and extreme drought events, a spatially coherent and consistent national drought library is required to improve consistency between estimates.

The national water resource supply demand model approach has sought to make the best use of the data contained within water company WRMP19 to illustrate the future challenges around public water supply across England. These challenges are significant but more work is required to have confidence in the scale of the challenge and the best approach to meeting that challenge.

3. The national framework modelling for options comparison

A national water resource supply-demand model with optimisation capabilities has been developed in collaboration with the University of Manchester. The study is aimed at examining the potential that different combinations of new water transfers and local water supplies have for satisfying national public water supply needs, under a range of different future demand scenarios. Fundamentally, this approach follows the same methodology by which we have estimated future challenges to supply and demand balances, as detailed in section 2. It is for this reason that the model is considered an aggregate model, relying on the high-level information output by water company simulation models, as opposed to digitally replicating the real-world behaviour of the company systems (i.e. simulation modelling).

Although the approach to framing the challenge is consistent with our national water resource supply-demand model, the way in which the options available to meet those future needs are compared, is taken much further. The University of Manchester's model was set up to search for the most efficient combination of transfers and local supply expansion options (e.g. reservoir, desalination) to meet future demand scenarios. In this way the model allows for a top down review of potential option selection; providing a strategic national level insight into the most efficient transfer options, and the scale of infrastructural development required to satisfy future water needs across England.

3.1. Modelling platform

The national water resource supply-demand model for option comparison was constructed using Pywr[6], an open source, python-based resource system simulator. Pywr is a tool for solving network resource allocation problems at discreet time steps using a linear programming approach. At each time step, water is allocated to different 'nodes' by minimising an 'allocation penalty'. The allocation penalty does not represent a real-world metric, but instead is used to direct the model's behaviour according to water management preferences.

Although Pywr is primarily designed to simulate water resource systems in detail, the flexible nature of the software means that it is readily adaptable and can therefore be employed to carry out the aggregate type modelling approach necessitated by the input data used in this study (annual supply-demand balances by water resource zone).

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[6] Tomlinson, J. E., Arnott, J. H., and Harou, J.J. (2020). A water resource simulator in Python. Environmental Modelling & Software, 126: 104635.

Furthermore, the speed at which Pywr can perform supply-demand balance calculations means that multi-criteria heuristic search (optimisation) algorithms [7](e.g. multi-objective evolutionary optimisation) can be connected to the model to search for promising decisions across the whole system. This functionality makes Pywr suitable for the purpose of this study; allowing for the identification of water resource system portfolios or plans that maximise system performance in multiple criteria, as well as, the quantification of the trade-offs between these criteria and how choosing different infrastructure investments impacts those trade-offs.

The approach used for modelling deficits, options and transfers using the 'aggregated' supply-demand balance dataset was first to run scenarios individually, for model validation and benchmarking, and then use more advanced capabilities, including linking to search algorithms. This process is outlined in the following sections.

3.2. Input data

3.2.1. Supply and demand

The model uses water resource management plan (WRMP) 2019 table-derived data, provided by the water companies, as input. Consequently the model formulation is high-level, running on an annual time step and with supply and demand aggregated at the water resource zone (WRZ) level. All of the WRZ's in England are included in the model, each represented by an individual model node, which is located at the centroid (geometric centre) of the zone. At each model node, the WRZ's demand is represented by distribution input (DI) plus headroom, whilst, its supply is represented by water available for use (WAFU). The components and sub-components for both parameters are listed in table 18.

Table 18: The components and sub-components used to parameterise demand and supply for each model node (WRZ)

Parameter	Component	Sub-component/Detail
Distribution Input (DI)	Household consumption	Per-capita consumption
		Population
	Non-household consumption	Measured
		Unmeasured
	Unbilled consumption	-
	Operation	-
	Leakage	See Scenarios (3.4.1)
	Fixed exports	-
	Headroom	Climate change
		Other
	Drought demand measures	-

[7] Maier, H. R., Razavi, S., Kapelan, Z., Matott, L. S., Kasprzyk, J., and Tolson B. A. (2019). Introductory overview: Optimization using evolution algorithms and other metaheuristics. Environmental Modelling & Software, 114, 195-213.

Parameter	Component	Sub-component/Detail
Water Available For Use (WAFU)	Baseline deployable output (DO)	DO of existing supplies
	Planned DO	DO of future supplies
	Outage	-
	Raw water losses	-
	Drought supply measures	-
	DO change	Sustainability reductions
		Climate change
		Other

3.2.2. Transfers

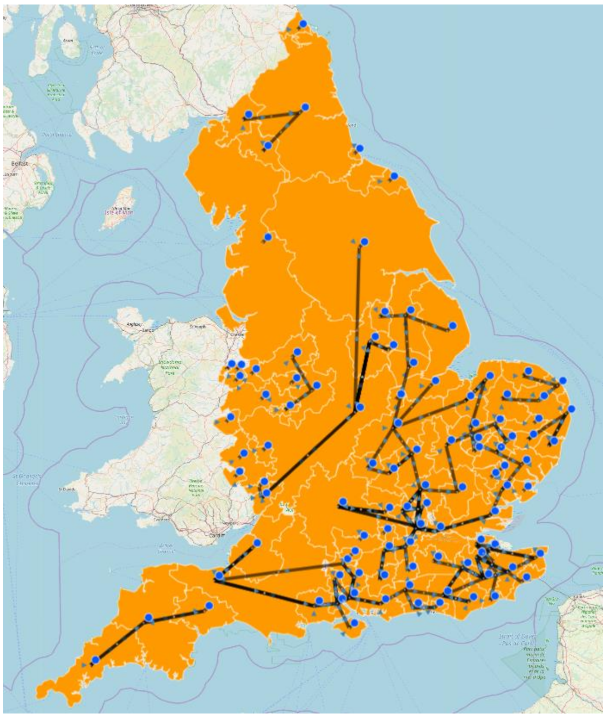
Existing and preferred transfers

Import and export transfer component information, from the WRMP tables, was reconciled to create a list of baseline (existing) and preferred transfers. This dataset was quality assured and validated through discussions with each company. The baseline transfers are used to inform the representation of current transfers in the model. Since the modelling baseline year is 2025 the 'existing' transfers in the model are a combination of those in the baseline of the water company plans, along with any preferred transfer options to be implemented by 2025. Conversely, preferred transfers are the transfer options from company plans that are implemented after 2025. The model is always configured to run with the existing transfers in place, however, the preferred transfers are only used in model setups involving heuristic searches[8].

Rather than including transfers in each WRZ's DO (i.e. fixing the volume transferred each year), the model is allowed to vary the volume and direction of water transferred. This is subject to, and limited by, there being a surplus in the donor WRZ and a deficit in the recipient WRZ(s). Information from the WRMP tables around maximum capacity (for dry year annual average) is used to set an upper limit on the transfer volume, and the direction of transfer is only allowed to vary for bi-directional schemes. This functionality is not an attempt at replicating the operational decisions and complexity associated with each transfer, but instead it helps avoid situations where transferring a fixed volume of water would either result in an unnecessary surplus in the receiving zone or create a deficit in the donor WRZ, which is increasingly likely when running the model under more severe demand scenarios. The model setup with existing and preferred transfers in place is shown in figure 20.

[8] 'Heuristic' searches in this case refer to the semi-optimal decision making that is produced from the optimisation component of the Pywr model – heuristic is a standard term that describes a practical approach to decision formulation and making. In this case it relates to the genetic algorithm search used in the modelling.

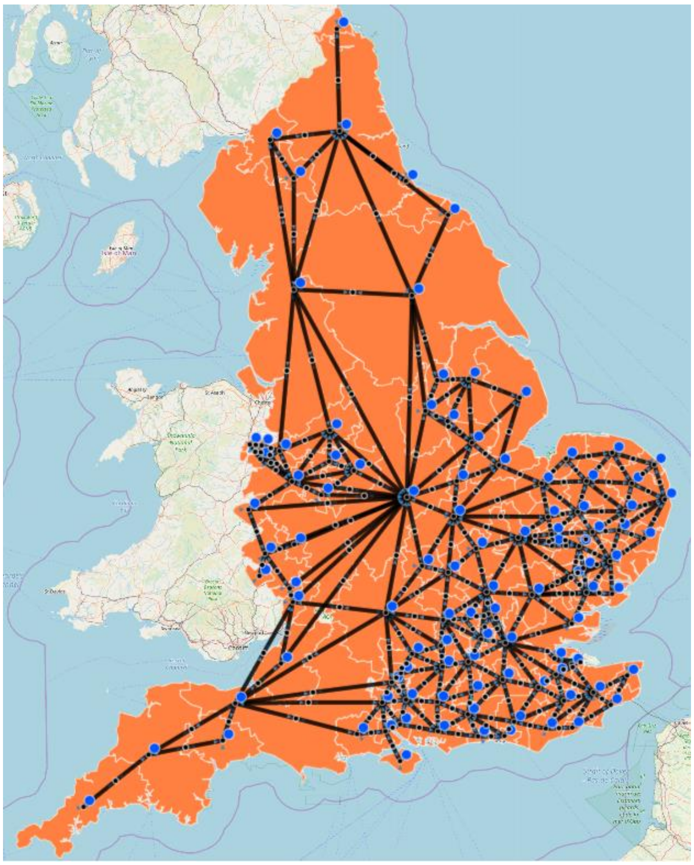
Figure 20: Visualisation of the model setup with existing and preferred transfers. Black lines = existing and preferred transfers; blue points = model nodes; orange polygons = WRZ boundaries. Note that the model nodes are positioned at the centroid of each WRZ and therefore the length and position of transfers does not represent reality but instead provides a visual conceptualisation of which WRZs are connected in the model.



Possible future transfers

In order to explore the use of transfers in satisfying national deficit, the model was set up with the ability to activate new possible transfers between WRZs. This functionality is built around a system of possible future transfers, which connect neighbouring WRZs to one another, as shown in figure 21.

Figure 21: Visualisation of the model setup with potential connections between all neighbouring WRZs. Black lines = possible future transfers; blue points = model node; orange polygons = WRZs.

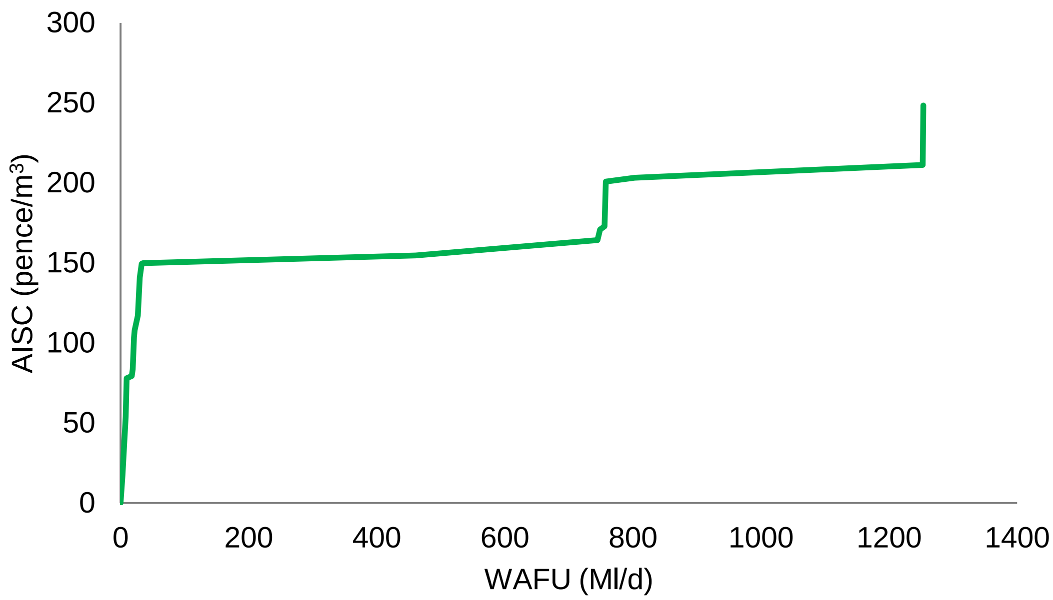


All of these possible transfers are available for the model to activate, however, during optimisation the models selection of which transfers to implement is driven by a penalty minimisation rule. This penalty is a proxy for cost and is calculated by summing the product of each activated transfer's capacity by the length of the transfer. The distance of each activated transfer is approximated as the distance between the model nodes (centroids of each WRZ). A higher volume distance transferred metric implies a higher volume of water being transferred over a larger distance, and vice versa. In this way, shorter and smaller transfers are used before longer larger ones.

3.3. New supply options

This study aims to investigate how the use of new local supplies compares with the use of transfers for minimising deficits. Information on the feasible and preferred new local supply options, for each WRZ, was compiled using the WRMP table data. For each WRZ, the average incremental social cost (AISC) of each option is ranked, lowest to highest, and cumulatively summed along with the associated new water available for use (WAFU). An example of the resulting AISC vs WAFU cost curve for a single WRZ is shown in figure 22. The cost curves provide a means for the model, during the search process, to make a supply expansion decision for each WRZ and determine the resultant supply cost.

Figure 22: Example average incremental social cost vs water available for use cost curve



When in supply expansion search mode, the model selects the volume of water required (WAFU) to meet demand from the cost curve for each WRZ, and then integrates to find the area beneath the curve up to that point, yielding the total cumulative AISC of supply expansion. Each WRZ's supply expansion cost is summed and the total supply cost is minimised in the search.

Supply options cost

The modelling work carried out with the University of Manchester investigates options portfolios involving transfers and local supply side expansion and is therefore predicated partly around a cost objective. In this way, the model is sensitive to the cost values for supply options presented in WRMP tables across the companies. A level of consistency is required in order for options to be compared on a like for like basis by the model. Audit of water company cost data highlighted a significant variation in net present value (NPV) and AISC for similar options. Much of this variability was found to be a function of the range of approaches that companies have taken to reporting/accounting for finance costs in the WRMP tables. While the WRP guidelines does allow for this kind of flexibility in completing the tables, it also means that a national collation of the data is not suitable for informing the National Framework modelling. A review of the AISC values presented in WRMP tables by the companies was therefore carried out to isolate and address these inconsistencies.

AISC values were recalculated using cost component data in the WRMP tables and following the method set out in our WRMP19 guidance. This follows the Spackman[9] approach to calculating finance costs and discounting, which includes the cost of capital as an explicit stream of annual costs, over the life of an option, alongside other project

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[9] Discounting for CBAs involving private investment, but public benefit, Joint Regulators Group (2012)

costs such as capex and opex. The approach takes explicit account of financing costs by converting investment (capital) cost into annual payments, given as a stream of financing costs, which are then discounted at the same rate as other costs. In many cases, option costs have been reported in the WRMP tables with the double counting of capex, as the net present value of fixed capex and variable capex is included in the AISC calculation, as well as the interest payments in the financial costs. So, in effect the AISC values for these options includes the cost to build and operate the options, plus the cost of interest payments to finance the borrowing. Re-calculating the AISC values for all options in WRMP tables resulted in a 30% reduction of variability for each option type, compared to the original company data.

AISC values for preferred and feasible supply side options (including: aquifer recharge, catchment management, conjunctive use, desalination, effluent reuse, groundwater enhancement, groundwater new, licence trading, new reservoir, surface water enhancement, surface water new – non reservoir and water treatment works new) were used as a decision variable to be minimised during optimisation in the national water resource supply-demand model for options comparison. While recalculating AISC values removes the double counting error associated with the way in which values were reported by companies in WRMP tables, a significant amount of variation still exists in the cost data for similar options between companies. Part of the variability is a function of the different approaches companies have taken toward asset life and renewal, however, the majority of the discrepancy is likely a result of fundamental differences in option unit costs and scoping methodology, plus variability in the scope of cost included for requirements such as ‘downstream’ infrastructure needs. Removing the variability observed in the cost information is beyond the scope of the National Framework modelling but should be considered as a source of uncertainty for the optimisation modelling process.

3.4. Model validation

Before the model is connected to a heuristic search (optimisation) algorithm and the output becomes complex, it must first be validated in order to sense check the results. Our national water resource supply-demand model described in section 2, is a spreadsheet tool based around the same input data and approach (i.e. aggregated supply-demand data from the WRMP19 tables) and therefore provides a point of reference for sense checking the supply-demand model described here. The University of Manchester’s model was set up to perform a static run (i.e. no optimisation) under the same scenarios tested in the national water resource supply-demand model.

Comparison of the supply-demand values output per WRZ for the 2050 planning horizon, shows an average difference of 10.39%, and a median difference of 5.15% between the two models across all demand scenarios (i.e. higher, central and lower scenarios). These relatively small differences are due to the University of Manchester’s model being able to choose the volume of water transferred at each time step, whereas the spreadsheet tool transfers a fixed volume. Similarly, the top-down approach used to account for the preferred supply options in the spreadsheet tool yields a small difference in DO, compared to the bottom-up approach used to inform the University of Manchester’s supply-demand model.

3.5. Multi-criteria search - options search (optimisation)

By connecting the model to a search algorithm (e.g. multi-objective evolutionary algorithm), every conceivable permutation of transfers and local supply options can be evaluated to find the different ‘cost’-efficient combinations that meet national water needs. This top-down approach for option selection is a high-level but nevertheless powerful means for identifying efficient (strategic) transfer pathways and demonstrates how different extents of water transfer usage would influence which local supplies would 'cost'-effectively meet future demand.

During the search process, the evolutionary algorithm iteratively tries out different planning strategies (e.g. selecting different local supplies and transfers) implemented by the model, which then outputs summary performance metrics. Some of these metrics are used as optimisation objectives, which the algorithm attempts to minimise (e.g. cost, deficit). The evolutionary algorithm selects "better" performing strategies and places them into an archive. As the search continues, more solutions enter the archive while those that are found to be inferior to the new ones are removed. The algorithm consequently applies variation operators (e.g. cross over and mutation) to these solutions, thereby creating new solutions that are then iteratively tested. The process is continued until the best possible strategies and their trade-offs are identified. The efficient or "Pareto-optimal" solutions (infrastructure portfolios) are those found whose performance cannot be improved in any single performance metric without degrading the performance in one or more objectives. This functionality mimics the process of natural selection and gives the evolutionary algorithm its name.

3.5.1. Search objectives and scenarios

Heuristic search functionality is implemented by connecting the national aggregate model to the Non-dominated Sorted Genetic Algorithm III (NDGA-III[10]), via the Platypus Python library[11]. The search algorithm varies the decision variables to best meet the objectives. In the problem formulation, the total new supplies within each WRZ and the activation of different transfers, for the year 2050, were the decision variables. The objectives were to minimise the resultant nationally aggregated cost and volume-distance transfer metrics (performance metrics) while attempting to satisfy the national deficit. It is important to note that under this formulation, the volume x distance transfer metric is minimised only for transfers between WRZs that are in different regional groups (i.e. inter-regional transfers). Transfers between WRZs in the same region (i.e. intra-regional transfers) were not included in the transfer x distance metric to specifically minimise cross regional transfers.

As the cost of constructing and operating new transfers that are not detailed in the WRMP is not currently known with any degree of accuracy, the assessment of potential transfer benefits was carried out by examining how the cost of other schemes reduced as the volume x distance metric increases. To accommodate for this approach, the search process first involves finding the lowest achievable supply cost for any given total transfer usage (characterised by the volume x distance metric) that satisfies any deficits nation-wide. The iterative search process is continued such that for any given level of one objective, the best achievable performance for another is found. These solutions map out a trade-off in performance space, which defines the lowest achievable national supply cost for any given level of transfer use. In this way, the analysis effectively demonstrates the avoided cost benefit of instigating the transfers, which can be later compared against the costs of those transfers once these become known (outside the scope of this report).

Searches were performed under three different demand scenarios, each with two different configurations of transfers. The resulting six searches are summarised in table 2. The scenarios represent lower, central and higher demand futures for public water supply with the central case aligning broadly with the ambition around demand set out by water

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[10] Deb K., and Jain, H. (2014). An Evolutionary Many-Objective Optimisation Algorithm Using Reference-Point-Based Nondominated Sorting Approach, Part I: Solving Problems With Box Constraints. IEE Transactions on Evolutionary Computation, 18(4).

[11] Platypus Python Library

companies in the WRMP19 planning round. These three scenarios are the same as in our national water resource supply-demand model (see section 2, table 16).

Table 19: The three scenarios and the two transfer configurations over which the multi-criteria search was performed

Parameter	Demand Scenario					
	Low demand		Central demand		High demand	
Transfers	Preferred (WRMP)	Potential	Preferred (WRMP)	Potential	Preferred (WRMP)	Potential
Resilience	1:500	1:500	1:500	1:500	1:500	1:500
Per capita consumption (PCC)	110 l/p/d	110 l/p/d	119 l/p/d	119 l/p/d	127 l/p/d	127 l/p/d
Non-household consumption (PWS)	4% Reduction	4% Reduction	No Change	No Change	No Change	No Change
Leakage	50% reduction	50% reduction	WRMP19	WRMP19	30% reduction	30% reduction
Demand side drought actions	2% saving	2% saving	2% saving	2% saving	2% saving	2% saving

Under the preferred transfer search model configuration, existing transfers and preferred transfers identified in the current water company plans are available for use. However, transferring via existing transfers does not affect the transfer x distance metric. The same applies for searches under the possible transfer model configuration, where existing transfers are available for use, but only the use (i.e. activation) of inter-regional transfers is quantified in the volume x distance metric.

3.5.2. Modelling assumptions

The national water resource supply-demand model for option comparison is a conceptual representation of reality and therefore has a formulation based around a range of associated assumptions and simplifications, including:

- new water transfers do not take into account the environmental or technical feasibility of implementation
- the distances used to inform the volume x distance metric, for both the preferred and potential transfer model configurations, are calculated between the centroid of each WRZ and therefore the transfer distance may be overestimated or underestimated, particularly for large WRZs with irregular shapes
- supply options with interdependencies (e.g. increased abstraction from a river and building a water treatment works) are not formally accounted for when building cost curves for each WRZ. This means that individual components of a compound option may be implemented
- for supply options that are non-unique (i.e. for which there are multiple permutations of the same option) the option with the maximum WAFU is used

- the cost curve is considered continuous, allowing options to be implemented to smaller capacities than defined in the WRMP tables. This only happens for the last supply option being considered on the cost curve. For example, if a WRZ needed 4 new supply options to meet demand, the 4th one could receive a partial implementation, while the relatively cheaper options 1-3 would be fully implemented

While some of the simplifications and approximations may appear significant, they are commensurate with the accuracy of the input data used in the modelling (see section 2). These assumptions are therefore appropriate for carrying out a high level, top down overview for highlighting areas of potential efficiency gains and guiding the direction of travel on policy at the regional and national scale.

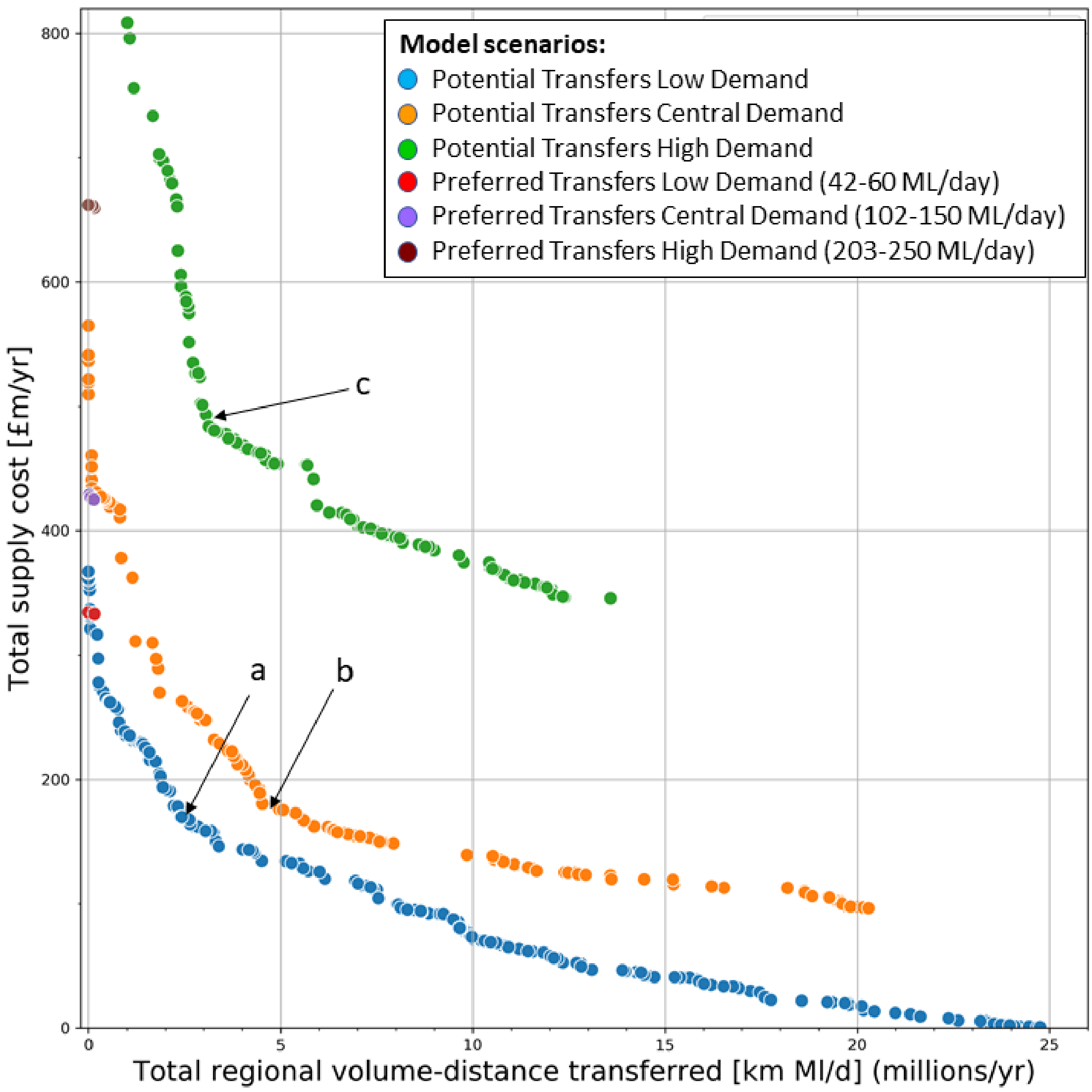
3.5.3. Identifying transfers that reduce supply costs

Minimising both the cost of local supply expansion and the volume x distance metric of new transfers generates a set of Pareto-optimal solutions. These solutions are portfolios of new supplies and transfers, at a national scale, which for any amount of water transfer usage (quantified by the volume x distance metric) minimise the cost of new supply expansion options and satisfy deficit. When plotted, this Pareto set of infrastructure portfolios maps out a trade-off curve between the two conflicting objectives/metrics (transfer usage vs. new supply costs). The six heuristic searches, carried out using the scenarios and model configurations outlined in table 19, produced separate trade-offs comprised of different supply expansion and transfer portfolios for the year 2050, which are shown in figure 23.

In general, as the demand scenario severity increases (i.e. higher PCC, lower leakage reduction, lower efficiency improvement), the solution portfolios require more transfer use for the same portfolio supply expansion cost to be maintained, and vice-versa. Higher values of either one of these metrics implies lower values in the other. The distance (in terms of supply cost) between the trade-off front for the lower and central demand scenarios is less than between the central and higher demand scenarios. This pattern suggests that a threshold is overstepped between the two scenarios, above which the cost of supply expansion and transfer use dramatically increases for the same increase in demand. Solution portfolios that plot toward the bottom right of figure 23 represent highly regionally interconnected portfolios (i.e. high inter-regional transfer volume x distance) and require less local supply investment. In these portfolios, WRZs with comparatively lower AISC local supplies implement their capacity expansion, generating a surplus that can be transferred to WRZs in deficit. Portfolios that plot towards the top left of figure 23 are those with more local supply investment and consequently less transfers (fewer and smaller transfers) as surpluses cannot be easily moved.

All solution portfolios identified under the preferred only transfer search model configuration have deficits of up to, 42-60 Ml/d, 102-105 Ml/d and 203-250 Ml/d under the lower, central and higher demand scenarios respectively. Results show that water surpluses in the north and west regions are ‘stranded’ under the preferred transfer configuration. In the low and central demand scenarios, portfolios overlap in the supply cost metric and volume x distance metric, with those identified under the possible transfer search model configuration. This trend implies that under these two demand scenarios, there could be scope to implement more efficient inter-regional transfers, at a similar scale (i.e. volume x distance) to the preferred transfers proposed in water company plans, that would satisfy the national deficit, for the same (in the low demand scenario) or similar (in the central demand scenario) local supply expansion cost. In both scenarios, some portfolios identified under the possible transfer search model configuration have higher supply costs than the portfolios from the preferred transfer configuration. This is a result of these portfolios being able to satisfy national deficit by a low volume x distance by using possible transfers, albeit at a high local supply expansion cost.

Figure 23: Trade-off plot showing the relationship between total local supply costs vs inter-regional volume x distance transferred. Points represent individual portfolios of supply options and water transfers in 2050. Colours denote the two transfer configurations and three demand scenarios under which the system was optimised (as defined in table 19). Portfolios labelled a, b and c are inflection points described in the inflection points section.



The solution portfolios of the preferred and possible transfer search model configurations, for the higher demand scenario, do not overlap in either objective. In particular, the relatively large gap in volume x distance (~2km Ml/d (millions/yr)) suggests that the higher demand scenario oversteps a threshold at which point the level of inter-regional transfer provided by the preferred transfers in insufficient given the availability of supply options to reduce national deficit. Unlike the preferred only transfer search model configuration, the possible inter-regional transfers avoid a deficit under the high demand scenario. This implies that while the national supply expansion capacity is sufficient to meet water needs under the higher demand scenario, greater inter-regional connectivity is needed for national demand to be satisfied. It should be noted that the higher demand scenario represents the uncertainty around a ‘worst case’ demand future. Similarly, the supply expansion options used in the model do not include the deferred options (i.e.

options discarded from company plans due to failing one or more criteria), some of which may become suitable under more extreme demand futures.

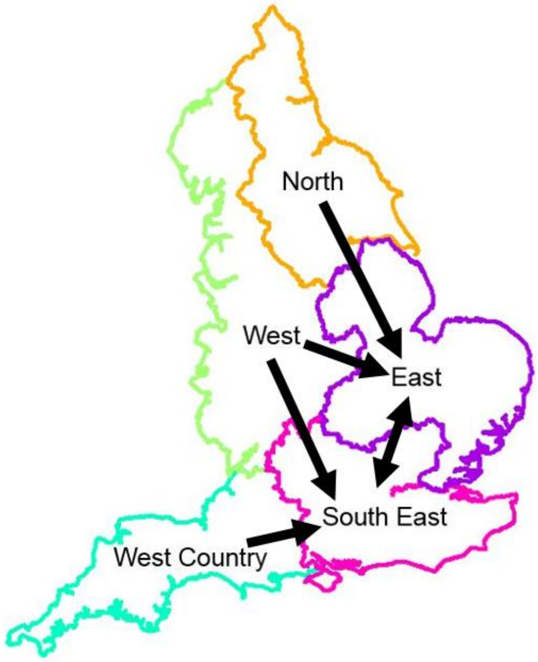
Inflection points

Inflection points are observed along the trade-off fronts in figure 23, for the possible transfer configurations of the low, central and high demand scenarios. These inflections occur when the slope of the trade-off front changes and show where the minor increase in one performance metric results in a marked decrease in another, or vice versa. Solution portfolios that plot to the right of the inflection points a b and c, marked on figure 23, show that relatively large decreases in the volume x distance metric result in small increases in cost of local infrastructure expansion.

These portfolios can be considered to have relatively lower value transfers, or excessively large capacity transfers. However, moving from bottom right to upper left along the trade-off curves, after the inflection points, ~3.0 km Ml/d (millions/annum), ~5.0 Ml/d (millions/annum) and ~2.5 km Ml/d (millions/annum) for the searches under high, central and low demand scenarios and possible transfers, respectively, additional decreases in regional transfers result in increasingly larger increases in local supply costs. The portfolios to the left of the inflection points contain transfers that that are able to strongly reduce the new water supply costs and can therefore be considered to play a strategic role. Some of these portfolios involve a similar transfer x distance metric to those identified for the same demand scenarios, under the preferred search model configuration. However, other portfolios, including those that plot on the steepest part of the trade-off curve and therefore contain the most efficient inter-regional transfers, involve significantly more transfer use than the new transfers identified in current water company plans. In the absence of an explicit economic transfer cost metric, it is difficult to assess whether these new transfers are cost effective relative to investing in more local supplies. This highlights the need for further work on the costing of potential future transfers.

A systematic analysis of the solution portfolios above the inflection points on figure 23 was carried out to identify possible strategic transfer routes, across all of the demand scenarios. These portfolios contain inter-regional transfers that help keep supply costs low. Identifying transfers common to all the portfolios is a means of isolating the most effective (i.e. strategic) transfers. The results are shown in figure 24, where the direction of the inter-regional transfers that occur most commonly in all the portfolios are represented diagrammatically. These involve transfers from water resource zones with surpluses in the north, west and west country to zones with deficits in the east and south east. The bi-directional transfer between the east and south east likely acts as a balancing transfer

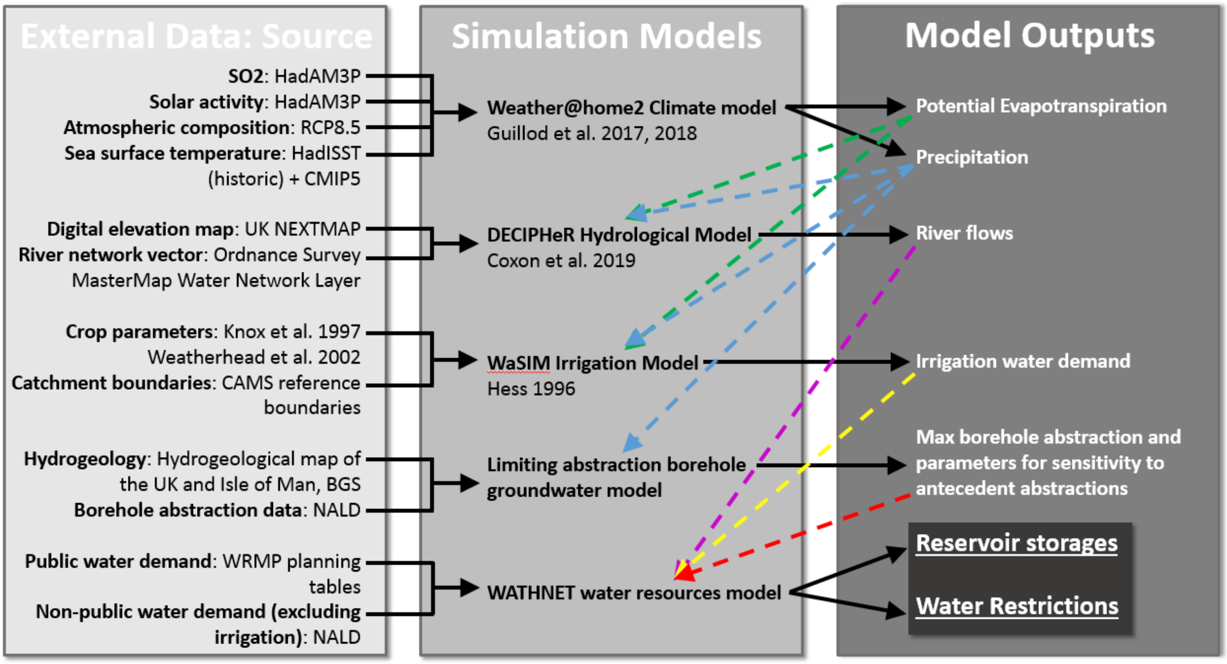
Figure 24: Inter-regional transfers that occur most commonly in all of the 'efficient' solution portfolios above the inflection points on the trade-off fronts for the low, central and high demand scenarios, under the possible transfer search model configuration (see points a, b and c on figure 23).



4. National framework simulation modelling

The University of Oxford have led a collaborative research project with the Environment Agency, also including the University of Bristol, Cranfield University, the Met Office and CEH Wallingford, which has developed a workflow for simulating droughts under climate change and the resilience benefits of strategic infrastructure schemes at a national scale. This study brings together a range of different datasets and simulation models, first investigating how the spatial and temporal characteristics of droughts are propagated from climatology to hydrology, and then using this to examine the impact on the water supply system. The process is summarised in figure 25, which illustrates how the outputs of some models are used as inputs for others.

Figure 25: Workflow overview showing the main data sources, models and outputs. Coloured dashed lines = model outputs that are used as input in other models.



4.1. Inputs for water resources modelling

4.1.1. Climate and hydrology

The workflow begins with ensembles of spatially coherent climate scenarios generated from the Weather@home2 modelling framework[12]. Previous projects have demonstrated that these ensembles of climate conditions are large enough to facilitate the investigation of risk and uncertainty, as well as, their spatial dynamics[13]. From this dataset precipitation and potential evapotranspiration are used from three spatially coherent scenarios:

100x45-year (1961-2005) baseline ensemble (that uses historic sea surface temperature (SST) and sea ice from HadISST[14] [15]

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[12] Guillod, B. P., Jones, R. G., Bowery, A., Haustein, K., Massey, N. R., Mitchell, D. M., Otto, F. E. L., Sparrow, S. N., Uhe, P., Wallom, D. C. H., Wilson, S., and Allen, M. R. (2017). Weather@home2: Validation of an improved global-regional climate modelling system. Geoscientific Model Development, 10(5), 1849-1872.

[13] Guillod, B. P., Jones, R. G., Dadson, S. J., Coxon, G., Bussi, G., Freer, J., Kay, A. L., Massey, N. R., Sparrow, S. N., Wallom, D. C. H., Allen, M. R., and Hall, J. W. (2018). A large set of potential past, present and future hydro-meteorological time series for the UK. Hydrology and Earth System Sciences, 22(1), 611-634.

[14] Rayner, N. A. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., and Kaplan, A. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. Journal of Geophysical Research: Atmospheres, 108(D14).

[15] Titchner, H. A., and Rayner, N. A. (2014). The Met Office Hadley Centre sea ice and sea surface temperature data set, version 2: 1 Sea ice concentrations. Journal of Geophysical Research: Atmospheres, 119(6), 2864-2889.

- 100x30-year (2020-2050) near future ensemble (that uses the 50th percentile SST and sea ice from CMIP5[16] using emission scenarios RCP8.5[17])
- 100x30-year (2070-2100) far future ensemble (that uses the 50th percentile SST and sea ice from CMIP5, using emission scenarios RCP8.5).

In order to be usable by the water resources model, the ensembles of precipitation and potential evapotranspiration produced from climate modelling, must be transformed into river flows. This is achieved using the DECIPHeR hydrological modelling framework, which can run large ensembles of climate simulations to provide spatially coherent, probabilistic flow simulations across multiple catchments with different hydrological characteristics[18].

4.1.2. Groundwater

The absence of a national scale groundwater model for abstraction makes hydrogeology difficult to parameterise. A linear empirical model was formulated to work around the problem which describes the maximum abstraction from a borehole in a given month dependent on antecedent rainfall and abstraction. This model is based on the groundwater licences in England's national abstraction licence database[19]. Both river flows and maximum available borehole abstractions are used as input into the national water supply model.

4.1.3. Water demand

Demand from public water supply is set at the water resource zone scale using information from the 2019 water resource management planning tables. The demand is approximated using the 'dry year annual average distribution input' metric, which is the expected yearly average water demand in a dry year, with a demand profile applied to give monthly water demand for each water resource zone.

A high percentage of water abstracted for public use is returned to rivers as treated effluent and forms an important role in water supply on rivers where abstractions occur in multiple WRZs (e.g. the River Severn, Trent and Thames). Effluent returns are represented in the model with the % consumed or returned based on information provided by water companies.

Non-public water supply demands are included at catchment scale and informed by Environment Agency abstraction data monthly from 1999-2015[14]. Demand is set as the average abstraction between 1999 and 2015. The abstraction data also contains information on the % of abstracted non-public water that is consumed vs returned. These values are used to inform where and how much water should be returned into the model downstream of an abstraction point.

Agricultural water demand outside irrigation is set using the same method for non-public water demands, as outlined above. In contrast, irrigation water demand is highly seasonal and dependant on climatology. The WaSIM simulation model is used to estimate irrigation

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[16] Taylor, K. E., Stouffer, R. J., and Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93(4), 485-495

[17] Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J.-F., Matsumoto, K., Montzka, S., Raper, S., Riahi, K., Thompson, A., Velders, G. J. M., and van Vuuren, D. P. (2011). The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change, 109(1-2), 213.

[18] Coxon, G.,et al. (2019). DECIPHeR v1: Dynamic fluxEs and Connectivity for Predictions of HydRology. Geoscientific Model Development, 12(6), 2285-2306.

[19] Environment Agency. (2015). National Abstraction Licence Database. Retrieved from https://data.gov.uk/dataset/f484a9be-bfd1-4461-a8ff-95640bf6bc3d/national-abstraction-licence-database-returns

water demand, which uses precipitation and evapotranspiration inputs from the weather@home2 seasonal in addition to crop and soil categorisation.

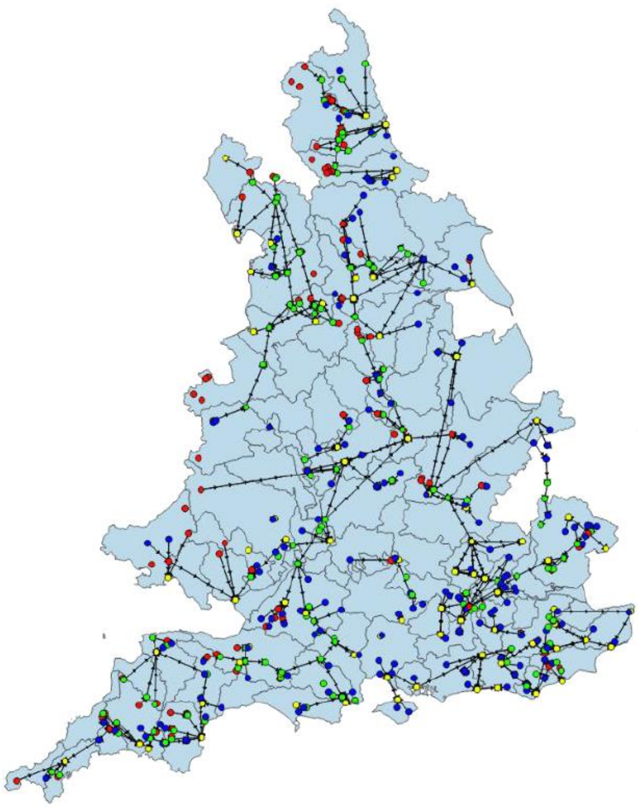
4.2. Water resource system modelling

4.2.1. The national water resource system model

A water resource system model of England and Wales, shown in figure 26, has been developed by the University of Oxford through collaboration with a range of stakeholders, including: the Environment Agency, UK-based water consultancies, Water UK, water supply companies and the regional water groups. The water system formulation in the model is based on communications with, and datasets provided by, these stakeholders. This 'digital twin' includes all major water supply infrastructure (reservoirs, boreholes, transfers, water treatment works, pumped storage, desalination plants and river abstraction points) that are connected to England's water network via any river or transfer > 2 Ml/d. It also includes abstraction licence conditions, operational preferences, control curves and asset locations for river abstractions and boreholes.

The geographic coverage of the model spans more than 90% of England and Wales' population and water demand; it contains 1252 nodes (reservoirs or abstractions) and 1756 arcs (e.g. rivers or transfers). While this study is aimed at investigating climate change impacts on water resources in England, many catchments straddle the border with Wales, and indeed some important water transfers originate from Wales (e.g. Elan Valley to Birmingham). Areas of Wales are therefore included to stabilise the model and are not subject to investigation for resilience under climate change.

Figure 26: The water resource system model, with modelled catchment boundaries shown in blue.



The model is simulated at a daily time-step using the water supply headworks simulation package WATHNET[20]. At every time-step, WATHNET solves a mass balance optimisation problem that allocates water between model nodes, via connections (known as arcs), under constraints inherent to mass balance (e.g. nonzero flows) and the formulation of the water system (e.g. infrastructural capacity). A set of costs associated with each model arc are minimised using a network linear programming solver. It is important to emphasise that costs are not real world economic costs but rather a model parameterisation used to approximate operator preferences and licences. The solver is run repeatedly each time-step to overcome potential issues with non-linearity and local minima. The model simulates all nodes (1252) and arcs (1756) at a daily time-step with a computational speed of ~2 minutes per year.

4.2.2. Strategic infrastructure options

One of the key aims of the national water resource system simulation model, is to examine how effective the strategic infrastructure options are at reducing the risk of water use restrictions under climate change. For this purpose, the water resource system model is configured in three ways; first, without any of the strategic schemes in place, secondly, with only certain schemes in place, and finally with all schemes in place. These model setups and the options involved are summarised in table 21.

Table 20: Summary of the options implemented for the likely/all options model configurations, set out to test the resilience benefits associated with different combinations of strategic infrastructure options. Strategic options are shown in bold. All other options are large (>20 Ml/d) supply options from WRMP19 plus two transfers tested in the water resources long term planning framework[21].

Option name	Company	Type of option	WAFU	Strategic option	WRMP19 option	Option configuration	
						Likely	All
Heathy Lee to North Nottinghamshire transfer solution	Severn Trent Water	Bulk Supply/Transfer	25	No	Yes	Yes	Yes
Ambergate to Mid Nottinghamshire transfer solution	Severn Trent Water	Bulk Supply/Transfer	30	No	Yes	Yes	Yes
Increase Grafham Import (+40 Ml/d)	Anglian Water > Affinity Water	Bulk Supply/Transfer	41	Yes	Yes	Yes	Yes

[20] Kuczera, G. (1992). Water supply headworks simulation using network linear programming. Advances in Engineering Software, 14(1), 55-60.
[21] Water resources long term planning framework (2015-2065), Water UK (2016)

Option name	Company	Type of option	WAFU	Strategic option	WRMP19 option	Option configuration	
						Likely	All
Grand Union Canal Transfer/Minworth	Severn Trent Water > Affinity Water	Bulk Supply/Transfer	50	Yes	No	Yes	Yes
Rutland Water to Affinity	Anglian Water > Affinity Water	Bulk Supply/Transfer	100	N/A (Water UK)	N/A (Water UK)	Yes	Yes
River Trent to Rutland	Severn Trent > Anglian	Bulk Supply/Transfer	200	N/A (Water UK)	N/A (Water UK)	No	Yes
River Severn to River Thames transfer scheme (Minworth, Vyrnwy and River Wye Support)	United Utilities	Bulk Supply/Transfer	500	Yes	No	No	Yes
Reculver RO Desalination of brackish groundwater	South East Water	Desalination	20	No	Yes	Yes	Yes
Desalination coupled to biomass-fuelled power plant	South East Water	Desalination	20	No	Yes	Yes	Yes
Tidal River Arun Desalination	Southern Water	Desalination	20	No	Yes	Yes	Yes
Desalination of River Medway tidal water at Aylesford/Snodland	South East Water	Desalination	30	No	Yes	Yes	Yes
Fawley Desalination – transfer to Testwood & Otterbourne WSWs & IOW	Southern Water	Desalination	75	Yes	Yes	Yes	Yes
Budds Farm Effluent Reuse	Portsmouth Water	Effluent Reuse	20	No	Yes	Yes	Yes

Option name	Company	Type of option	WAFU	Strategic option	WRMP19 option	Option configuration	
						Likely	All
Effluent reuse to River Ouse: source – Peacehaven	South East Water	Effluent Reuse	25	No	Yes	Yes	Yes
Site E expansion and transfer main supported by raw water augmentation of the River Trent	Severn Trent Water	Effluent Reuse	35	No	Yes	Yes	Yes
Reuse: Beckton (3 phases)	Thames Water	Effluent Reuse	300	Yes	Yes	No	Yes
GWE Franklaw	United Utilities	Groundwater Enhancement	27	Yes	Yes	Yes	Yes
Peacehaven WWTW Indirect Potable Water Reuse	Southern Water	Indirect Potable Water Reuse	20	No	Yes	Yes	Yes
Ford WWTW Indirect Potable Water Reuse	Southern Water	Indirect Potable Water Reuse	20	No	Yes	Yes	Yes
Havant Thicket Reservoir	Portsmouth Water	Reservoir	23	No	Yes	Yes	Yes
East Midlands third party raw water storage assed including WTW	Severn Trent Water	Reservoir	45	No	Yes	Yes	Yes
South Lincolnshire reservoir	Anglian Water	Reservoir	113	Yes	No	No	Yes
Abingdon – Transfer to London	Thames Water	Reservoir	251	Yes	Yes	Yes	Yes

In addition to varying degrees of complexity, some strategic schemes are further along the development pathway than others. Both of these factors mean that a disparate mix of information is available about the schemes, with which to inform the model. Nevertheless, the representation is sufficiently detailed to be considered valid on an absolute basis and therefore test the resilience benefits associated with implementation of major infrastructure options for water supply.

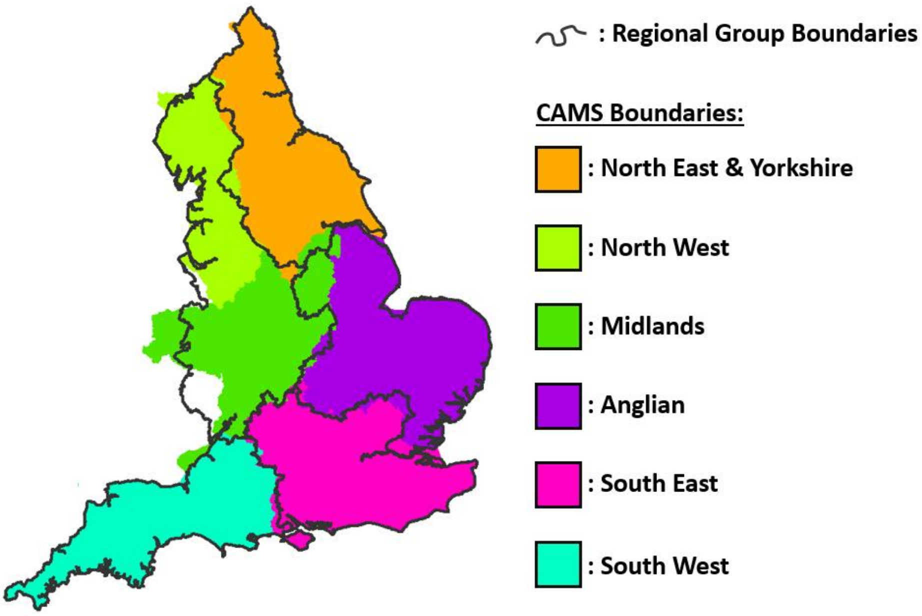
4.2.3. Model outputs

Model outputs are expressed as projections of reservoir storage and the frequency, severity and duration of water use restrictions. Reservoir storage is a good indicator for the state of water resources at a given time since drought measures are typically enacted when the storage of key reservoirs in the region is below a given value (that varies from reservoir to reservoir). Over 70% of the river catchments included in the national water resource system model contain a reservoir, and therefore storage time series is a valuable and spatially representative metric for examining water resources drought.

The second model output is water use restrictions; these are imposed to mitigate the effect of drought, typically when reservoir storage is low, and hence provide a more tangible metric of actual disruption than storage. In this study, a drought year is defined as a hydrological year (October to October) with one or more days of level 3 or 4 restrictions.

Results are reported using the regional boundaries from the Environment Agencies Catchment Abstraction Management Strategy[22]. These broadly correlate with the regional group boundaries, as shown in figure 27, with the exception of the Midlands and North West CAMS region which combined make up Water Resources West regional group.

Figure 27: Comparison of the regional group boundaries vs the Environment Agency catchment abstraction management Strategy regional boundaries



4.2.4. Modelling assumptions

The national water resource system simulation model is a conceptual representation of reality and therefore has a range of associated assumptions, many of which stem from necessary simplification of a complex system. Some of these modelling assumptions are directly informed by water companies:

- In some locations, multiple reservoirs that supply a single water treatment works have been aggregated together.

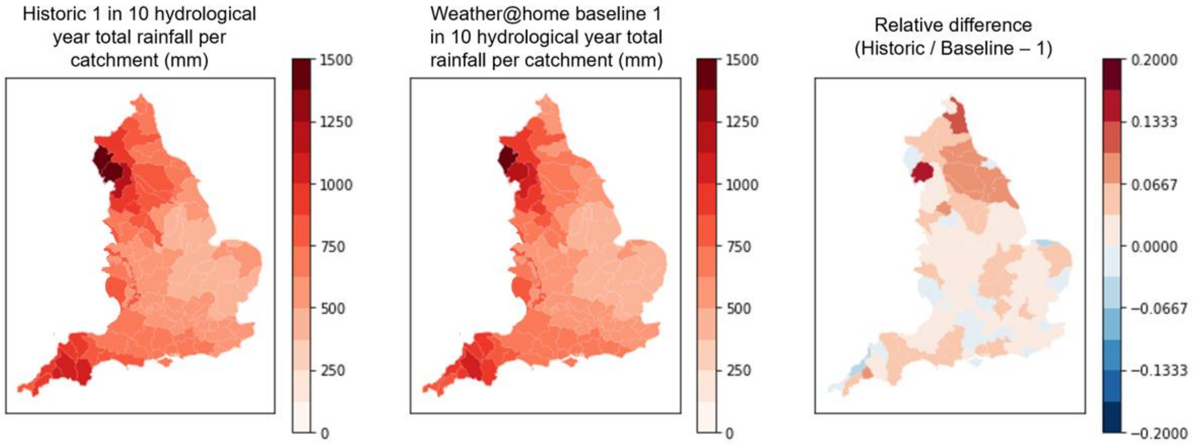
[22] Environment Agency. (2019). Catchment Abstraction Management Strategy (CAMS) Reference boundaries. Retrieved from https://data.gov.uk/dataset/e89f134c-f335-48e5-8d02-ald467ce6996/catchment-abstraction-management-strategy-cams-reference-boundaries.

- The redistribution of water in the modelled distribution network is represented by allowing multiple sources/transfers to deliver water to the same demand node.
- Small sources (< 1 Ml/d) have been omitted due to the constraints of integer programming.
- While others are a result of data availability:
- Water transfer along links (arcs) in the model is considered instantaneous, except for large aqueducts, whose flow travel times are known.
- Reservoirs have zero evaporation (except for a few large surface area reservoirs for which an evaporation relationship is well described).
- Water quality is not modelled but instead assumed to be always acceptable provided the volumetric licence conditions and minimum flow requirements in rivers are met.
- Decision rules and preferences governing operation of the water supply system are a simplification of the many considerations taken into account, especially during drought conditions.

4.2.5. Calibration and validation

To ensure that the methodology can be considered relatively robust over the large temporal scales involved, the climate modelling outputs (rainfall) and water resources simulation results (reservoir storage) from the weather@home2 baseline ensemble are compared with historic observation. Historical climate observations of precipitation and potential evapotranspiration are taken from CEH-GEAR[23] and CHESS[24], respectively.

Figure 28: Left and centre panels show the 1 in 10 hydrological year accumulated rainfall per catchment for both the historic (1890-2015 from CEH-GEAR) and weather@home2 baseline ensemble (30 x 1962-2006). Right panel: the difference between the two.



The historic climate data is first compared with the weather@home2 baseline. Figure 28 shows that the 1 in 10 total accumulated rainfall over a hydrological year is reasonably well modelled by the weather@home2 baseline. The only catchments with greater than 10% difference are high elevation regions, which are expected since the climate model cannot account for orographic precipitation (i.e. rainfall created by topography).

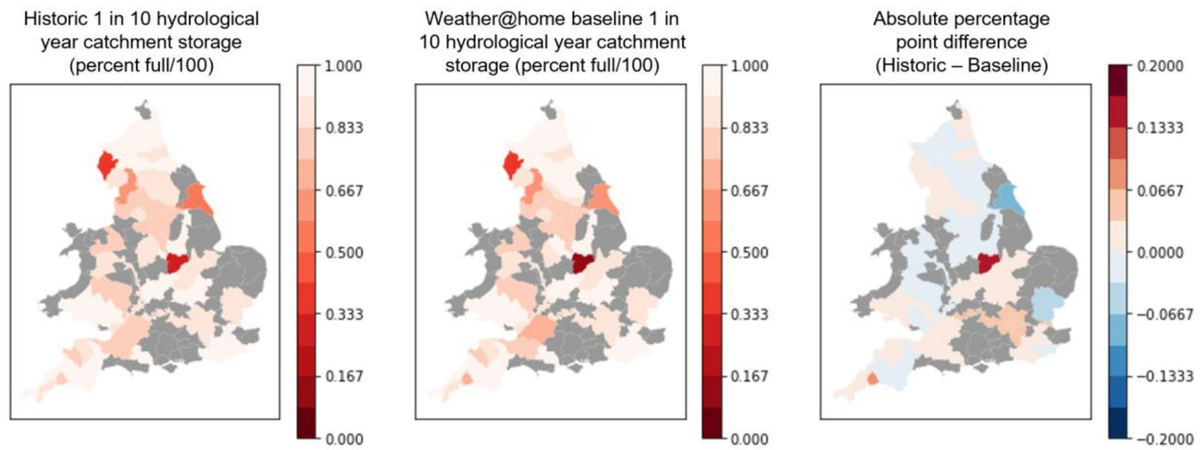
---

[23] Tanguy, M., Dixon, H., Prosdocimi, I., Morris, D. G., and Keller, V. D. J. (2016). Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890-2015) [CEH-GEAR].

[24] Robinson, E. L., Blyth, E., Clark, D. B., Comyn-Platt, E., Finch, J., and Rudd, A. C. (2016). Climate hydrology and ecology research support system potential evapotranspiration dataset for Great Britain (1961-2015) [CHESS-PE]. In NERC Environmental Information Data Centre.

Reservoir storage values simulated using the historic flow (i.e. outputs of the hydrological model forced by CEH-GEAR and CHESS PE between 1961 and 2015) are then compared with those from using the baseline flows (i.e. outputs of the hydrological model forced by the weather@home2 baseline ensemble, 30 x 1975-2005). The results are shown in figure 29, which suggest that the differences in rainfall seen in figure 28 do not translate to any significant difference in storage. The difference in 1 in 10 hydrological year storage between the historic and baseline ensemble is generally less than three percentage points of total volume. The catchment that is darkest red (i.e. storage is near empty-empty) in all of the panels, contains a small volume (< 5000 Ml) reservoir that is used in a balancing capacity and therefore has a storage that is highly variable

Figure 29: Left and centre panels show the 1 in 10 hydrological year reservoir storage in a catchment under historic and baseline flows, respectively. Storage is normalised between total active storage (1 = full) and dead storage (0 = empty). Right panel shows the difference between the two where red indicates the baseline has less storage and blue indicates the baseline has more storage.



Reservoir storage values simulated using the historic flow (i.e. outputs of the hydrological model forced by CEH-GEAR and CHESS PE between 1961 and 2015) are then compared with those from using the baseline flows (i.e. outputs of the hydrological model forced by the weather@home2 baseline ensemble, 30 x 1975-2005). The results are shown in figure 29, which suggest that the differences in rainfall seen in Figure 28 do not translate to any significant difference in storage. The difference in 1 in 10 hydrological year storage between the historic and baseline ensemble is generally less than three percentage points of total volume. The catchment that is darkest red (i.e. storage is near empty-empty) in all of the panels, contains a small volume (< 5000 Ml) reservoir that is used in a balancing capacity and therefore has a storage that is highly variable.

Figure 30: The distribution of drought year severity and probability for the historic and weather@home2 baseline scenario. Bars represent the distribution of days of restriction during drought years for a given region, with the box covering the 25th-27th percentile, whiskers extending to 1.5 times the interquartile range and 'outliers' indicated by circles. The position on the y-axis represents the probability of there being drought for a given region. Demand nodes (generally a water resource zone) with 3 or fewer drought years show points only.

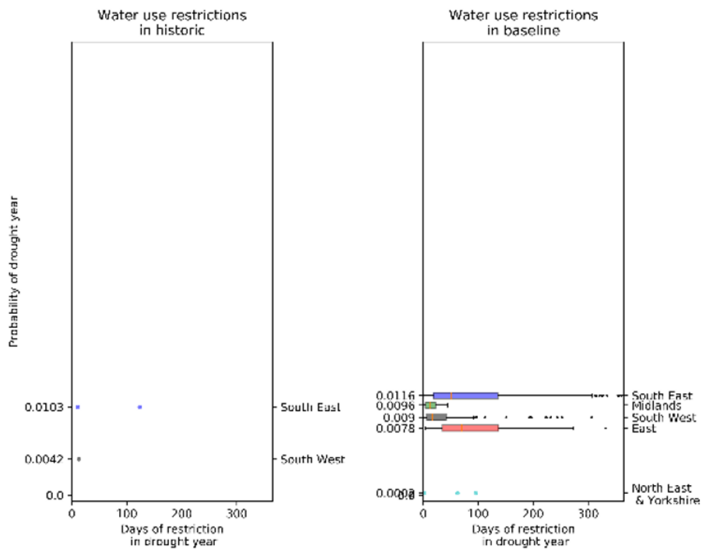


Figure 30 compares the distribution of drought year severity and probability for the weather@home2 baseline to restrictions projected in the historic period simulation. Because the weather@home2 baseline is a very long simulation, it contains many more synthetic droughts. It is therefore difficult to compare with the historic period, in which restrictions are rare. However, the estimated frequencies and durations of restrictions in the historic period are within the distribution simulated weather@home2 dataset. Though there are inevitable differences because of the approximations in the simulation modelling (summarised above), the modelling is sufficiently detailed to be considered valid on an absolute basis, and demonstrates that climate change is likely to significantly increase the frequency of drought interventions.

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